INTERACTION BETWEEN PROCESS ARCHITECTURE AND SOLVENT PROPERTIES FOR AMINE-BASED CO_2 CAPTURE

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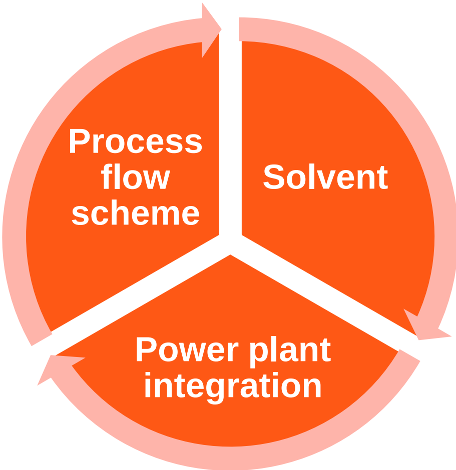
CONTEXT & OBJECTIVE

A challenge for post-combustion CO_2 capture :
reduce both energy penalty and cost of avoided CO_2

Literature focus individually on

- Solvent development and characterization
- Modifications of the process flow scheme
- Heat integration with power plant



In this study

- The three aspects are considered together
- An automatic methodology is developed, based on
  - Rigorous calculation of process performance
  - Use of an non-linear optimization algorithm, with LCOE as objective function
  - Simultaneous optimization of design and operating parameters

TYPE OF AMINE SOLVENTS

KEY MESSAGE

Process performance strongly depends on the specific physicochemical properties of the solvent

Type of solvent according to physicochemical properties

- Reaction kinetic
- Heat of absorption
- Resistance to degradation
- Cyclic capacity
- Transport properties
- Environmental aspects
- ….

Example of popular solvents and approximate values of most influent properties for a standard process

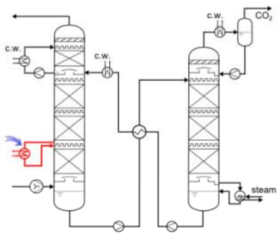
Solvent	MEA 30 wt%	AMP 30 wt%	MDEA 30 wt%	AMP+PZ 15+15 wt%	MDEA+PZ 15+15 wt%
Kinetic constant, $\log(k_{App})$ [s^{-1}]	4.6 (+)	3.3 (=)	1.3 (−)	5.1 (+)	5.1 (+)
Heat of absorption $\Delta_{abs}H$ [$kJ.mol^{-1}$]	80-85 (−)	50-90 (=)	45-60 (+)	60-90 (=)	60-80 (=)
Cyclic capacity $\Delta\alpha$ [$mol_{CO2}.mol_{Am}^{-1}$]	0.25 (=)	0.5 (+)	0.2 (=)	0.4 (+)	0.35 (+)
Thermal degradation at 140°C [% per week]	5.3 (−)	0 (+)	1.7 (=)	0 + 0.25 (+)	1.7 + 0.25 (=)

Data from Dubois et Thomas (2012), Lepaumier (2008), Aronu et al. (2011), Chen et al. (2011), Dash et al. (2012)

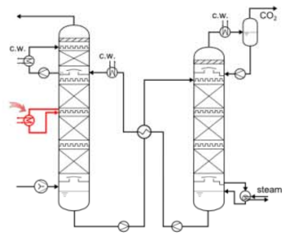
OVERVIEW OF SINGLE PROCESS MODIFICATIONS

Absorption enhancement

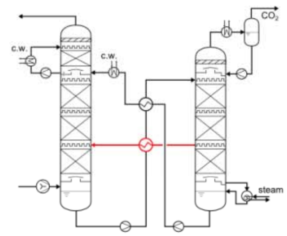
InterCooled Absorber (ICA)



InterHeated Absorber (IHA)

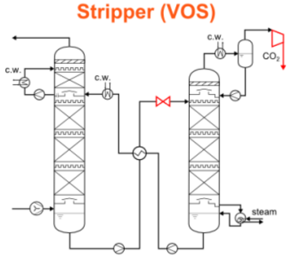


Split Flow Arrangement (SFA)

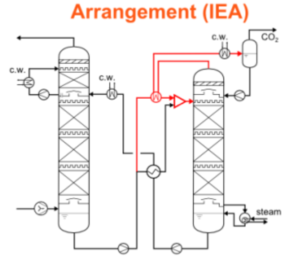


Heat integration

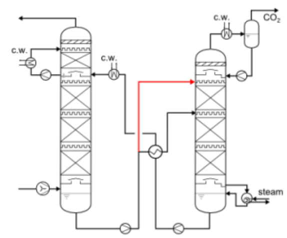
Vacuum Operated Stripper (VOS)



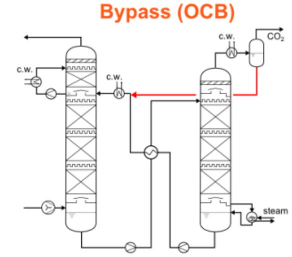
Improved Economizer Arrangement (IEA)



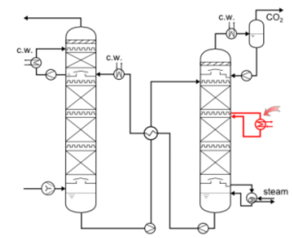
Stripper Split Feed (SSF)



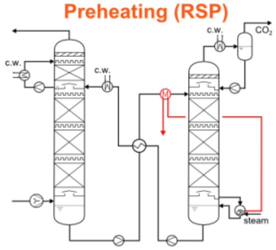
Overhead Condensate Bypass (OCB)



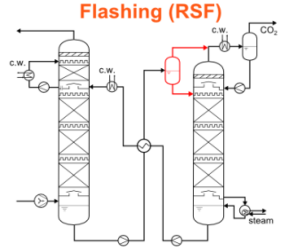
InterHeated Stripper (IHS)



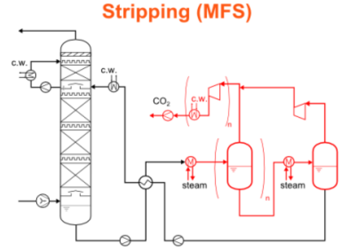
Rich Solvent Preheating (RSP)



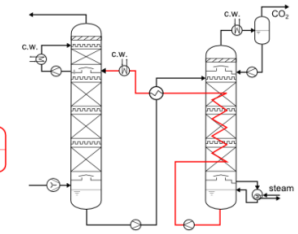
Rich Solvent Flashing (RSF)



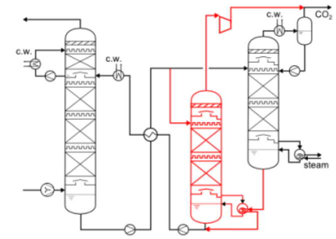
Multistage heated Flash Stripping (MFS)



Heat Integrated Stripper (HIS)

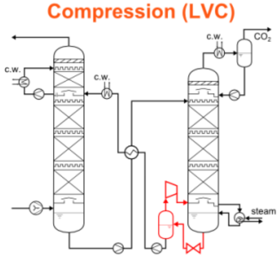


Multi Effect Stripper (MES)

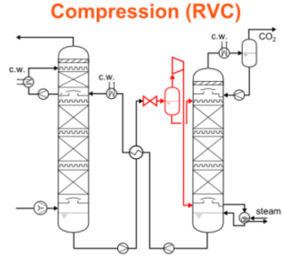


Heat pumps

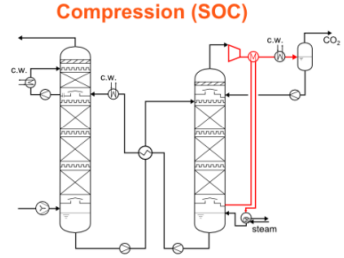
Lean Vapor Compression (LVC)



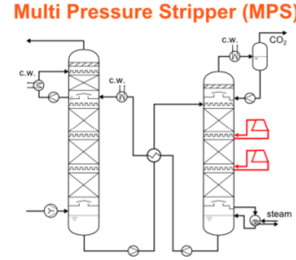
Rich Vapor Compression (RVC)



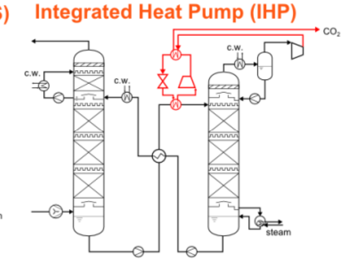
Stripper Overhead Compression (SOC)



Multi Pressure Stripper (MPS)



Integrated Heat Pump (IHP)



METHODOLOGY USED FOR PROCESS EVALUATION

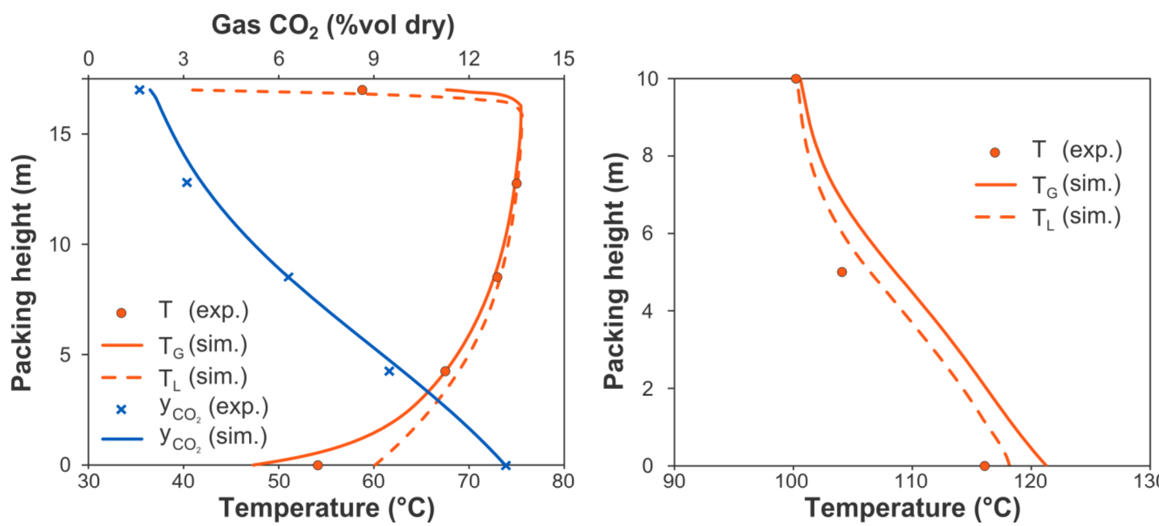
Phenomenological modeling[1]

- In-house simulation and optimization tool (in Fortran)
- e-UNIQUAC model for electrolyte solutions
- Rate-based formulation for heat & mass transfer
- Chemical enhancement in liquid film

→ Absorption & stripping models validated against literature data (Esbjerg and NTNU pilot plants)

Evaluation of energy penalty

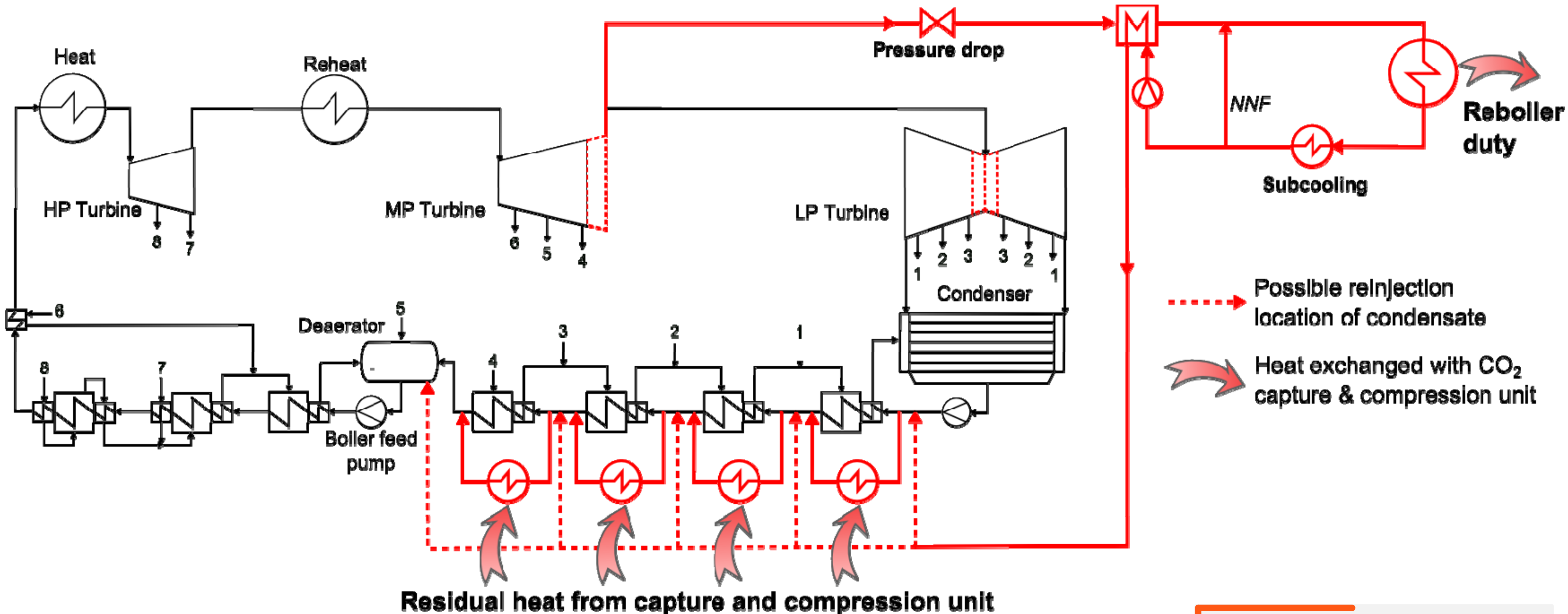
- Total equivalent work (kWh/t_{CO2}), including
  - Parasitic load (reboiler duty + vapor quality)
  - CO_2 compression work up to 110 bars
  - Auxiliary work of capture unit (e.g. pumps, fans, additional compressor)
  - Heat integration between power plant and capture unit
- Derivation of new correlations



Validation of absorber (left) and stripper (right) packing model on Esbjerg pilot data

[1] *Neveux et al., 2013. Ind. Eng. Chem. Res., 52:4266-4279*

THERMAL INTEGRATION WITH POWER PLANT



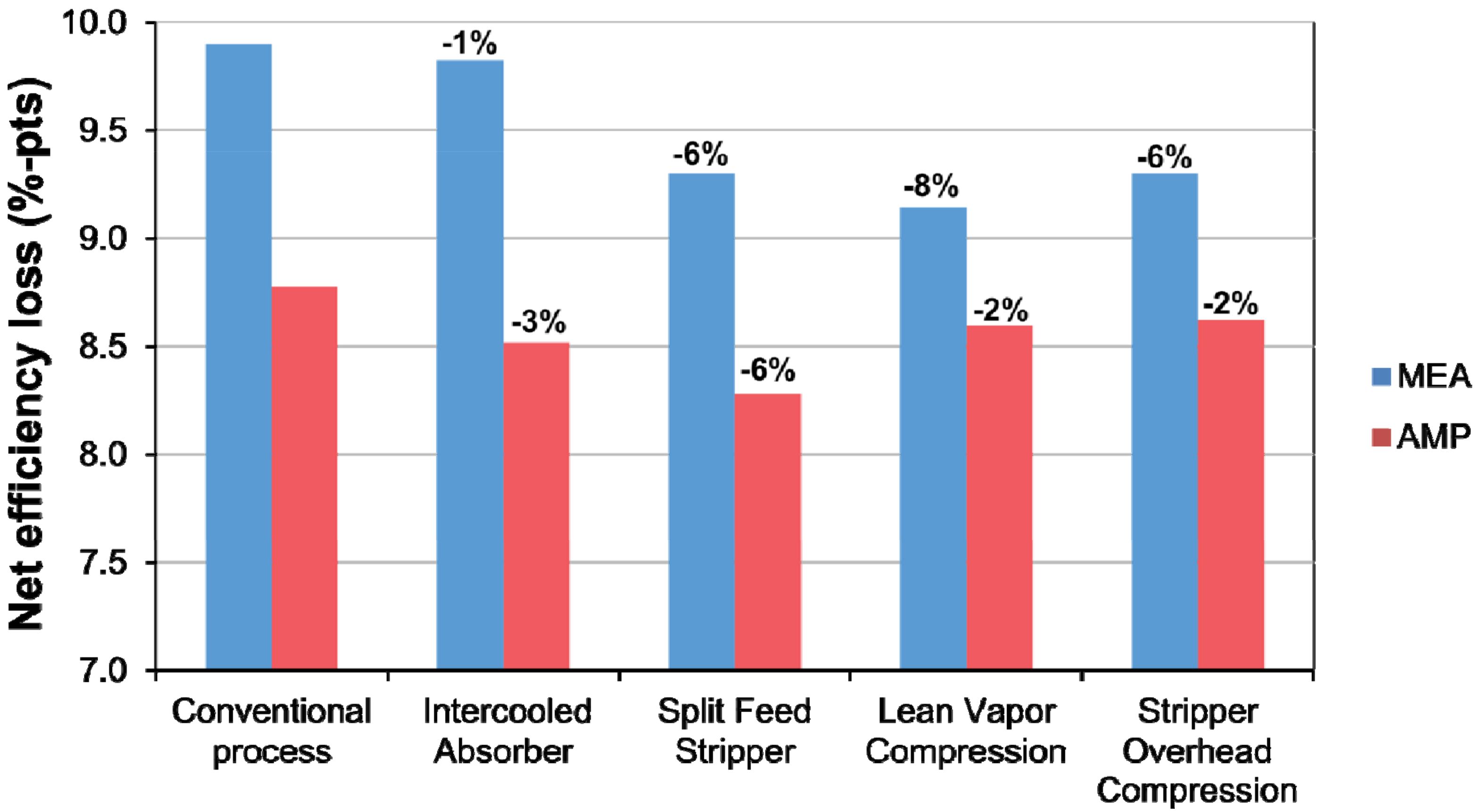
Integration strategy between capture unit and power plant

- Steam extraction at the required pressure level
- Steam desuperheating with the reboiler condensate
- Reinjection in the feedwater preheaters at the proper temperature level
- Subcooling of reboiler condensate possible (for some particular capture processes)
- Residual heat of capture and compression unit integrated into feedwater preheaters

An **advanced integration strategy** for new-built power plants

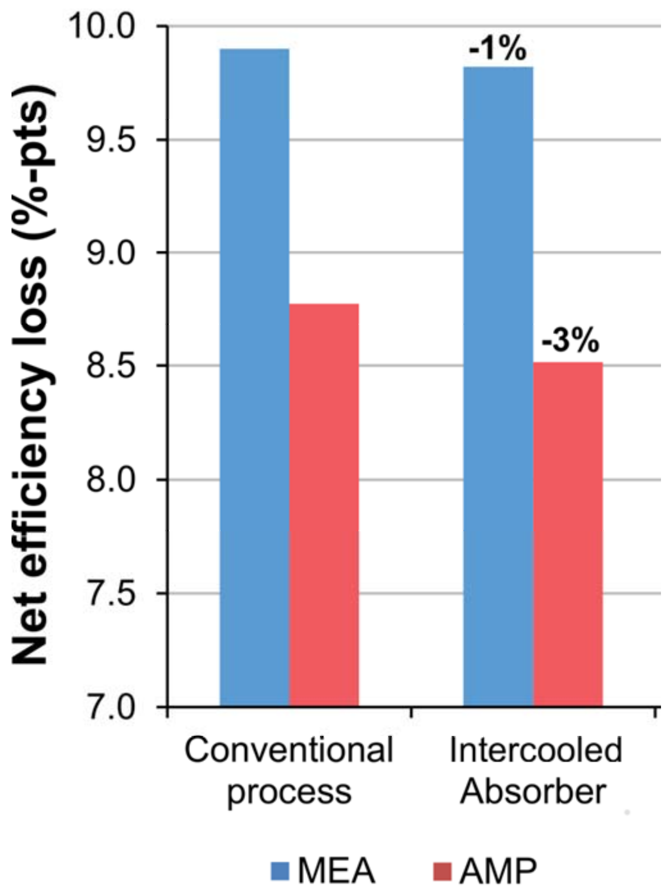
ENERGETIC SIMULATION RESULTS FOR MEA & AMP

- **Conventional process + 4 process modifications evaluated for 30wt% MEA & 40wt% AMP solutions**
  - Process equipment designed with chemical engineering heuristics
  - Operating parameters optimized with respect to energy penalty with a dedicated algorithm (fixed design)



Energetic simulation results of five flow schemes (percentages are reductions with respect to conventional process)

COMMENTS ON LIMITING PHENOMENA



MEA to AMP shift

- Lower heat of absorption
- Higher cyclic capacity → sensible heat reduced
- But higher absorber required

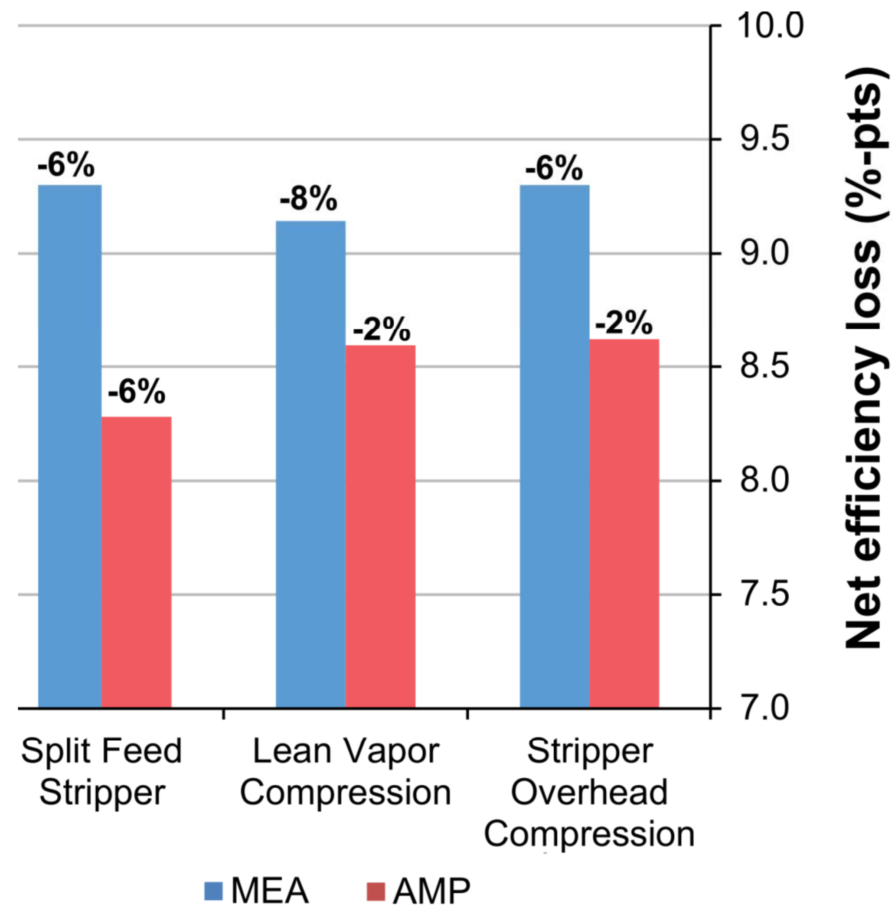
Absorption enhancement

- Absorber intercooler favor driving force
- More efficient for AMP (3% reduction) than for MEA (1%)
- Efficient for thermodynamic-driven mass transfer

COMMENTS ON LIMITING PHENOMENA

- **Heat integration (Split Feed Stripper)**
  - Improve heat exchange in economizer
  - pre-condensate steam in stripper top
  - Generic enhancement, efficient for both amine (6%)

- **Heat pump effect (Lean Vapor Compression & Stripper Overhead Compression)**
  - Rise heat quality through mechanical work
  - Generate steam to provide part of reboiler duty
  - More efficient for MEA (6-8%) than for AMP (2%)
  - Efficient for high heat of absorption solvents



NEED FOR A SYSTEMATIC OPTIMIZATION

Limitations of energetic approach

- Only production loss is evaluated
- No consideration of additional CAPEX
- No consideration of other OPEX (e.g. solvent loss)

Need to consider both **CAPEX** and **OPEX**

→ **LCOE**

→ **Cost of avoided CO_2**

A global technical-economic approach

- Numerous parameters → need for a systematic method
- **Simultaneous optimization of design and operating parameters**
- NLPQLP[1] method used for non-linear optimization

Technical-economic assumptions for cost estimation[2]

- Supercritical pulverized coal
  - Simulated with recommendations from EBTF
  - Equipped with SCR, ESP and FGD
  - 46.1 $\%_{LHV}$, 1082 MW_{gross}, 975 MW_{net}, 755 t_{CO2}/h
- 90% CO_2 capture, amine post-combustion
- LCOE evaluated in constant $€_{2011}$
- *N*th-of-a-kind plant, 40 years lifetime
- 7600 operation hours per year
- 8% discount rate, no inflation
- Fuel price = 10 €/MWh_{LHV}
- TOC = 1.9 x Installed Cost
- Contingencies = 10% x EPC
- No transport and storage cost considered

[1] *Dai et Schittkowski, 2008. Pacific Journal of Optimization*, 4:335–351,

[2] *In compliance with Rubin et al., 2013. Int. J. Greenh. Gas Con., 17:488-503*

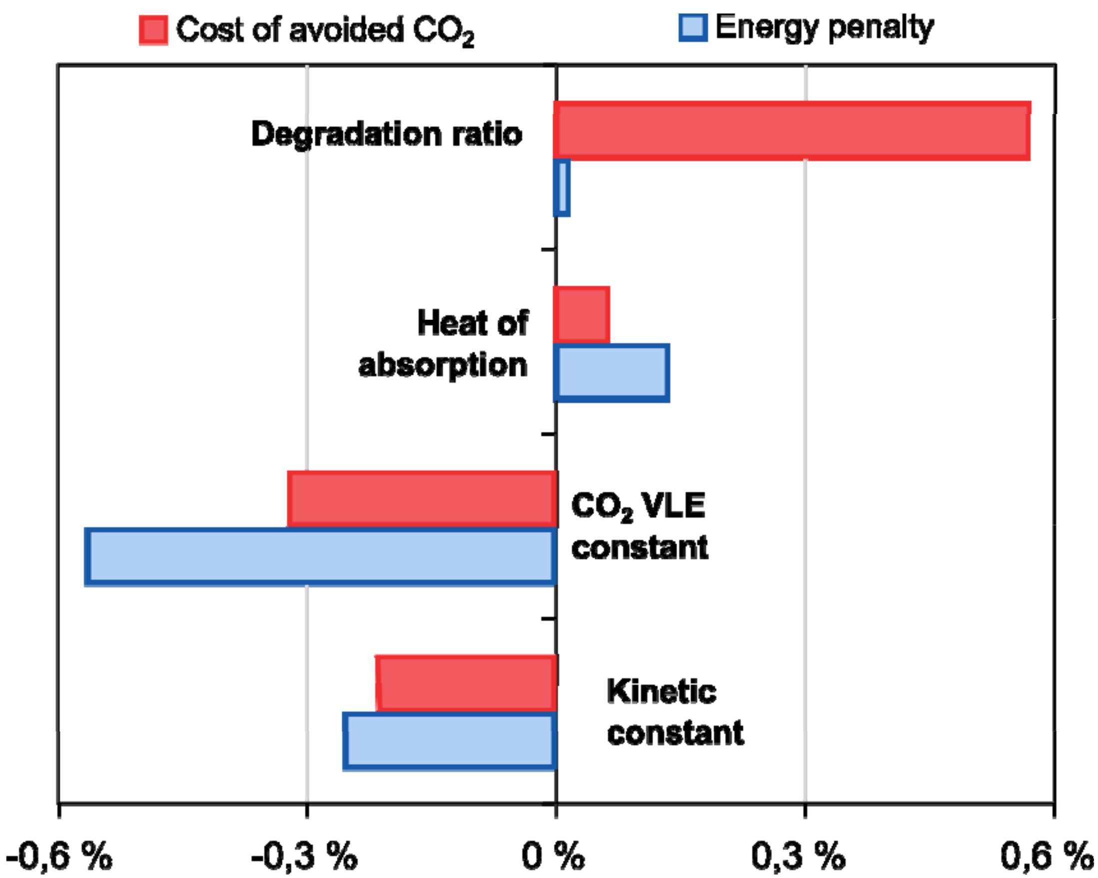
OPTIMAL DESIGN OF A CONVENTIONAL PROCESS

Design parameters	**Original**	**Optimized**	
Absorber height (Z_{abs})	15 m	→ 20.0 m	→ allow to maximize rich loading
Stripper height (Z_{strip})	10 m	→ 16.2 m	→ higher to provide pre-condensate area due to relatively cold rich solvent inlet (cf. economizer)
Economizer pinch (ΔT_{eco})	10 K	→ 28.1 K	→ reduce eco. CAPEX & provide colder rich solvent
Reboiler pinch (ΔT_{reb})	10 K	→ 5.7 K	→ trade-off CAPEX/OPEX favorable to OPEX
Condenser pinch (ΔT_{cond})	10 K	→ 5.0 K	→ trade-off CAPEX/OPEX favorable to OPEX
Operating parameters			
Lean loading ratio (α_{lean})	0.24	→ 0.20	→ lower solvent flow rate, reducing equipment sizes
Reboiler pressure (P_{reb})	2.1 bar	→ 2.1 bar	→ limitation due to solvent degradation
Energy penalty	9.9 %-pts	→ 8.5 %-pts	
Cost of avoided CO_2	100 %	→ 91 %	

Optimal design parameters are quite “unusual”

- Mainly due to power plant integration → favor cold rich solvent at stripper top
- Substantial energy gain 1.4 %-pts and reduction of cost of avoided CO_2 of 9 %

SENSITIVITY TO SOLVENT PROPERTIES



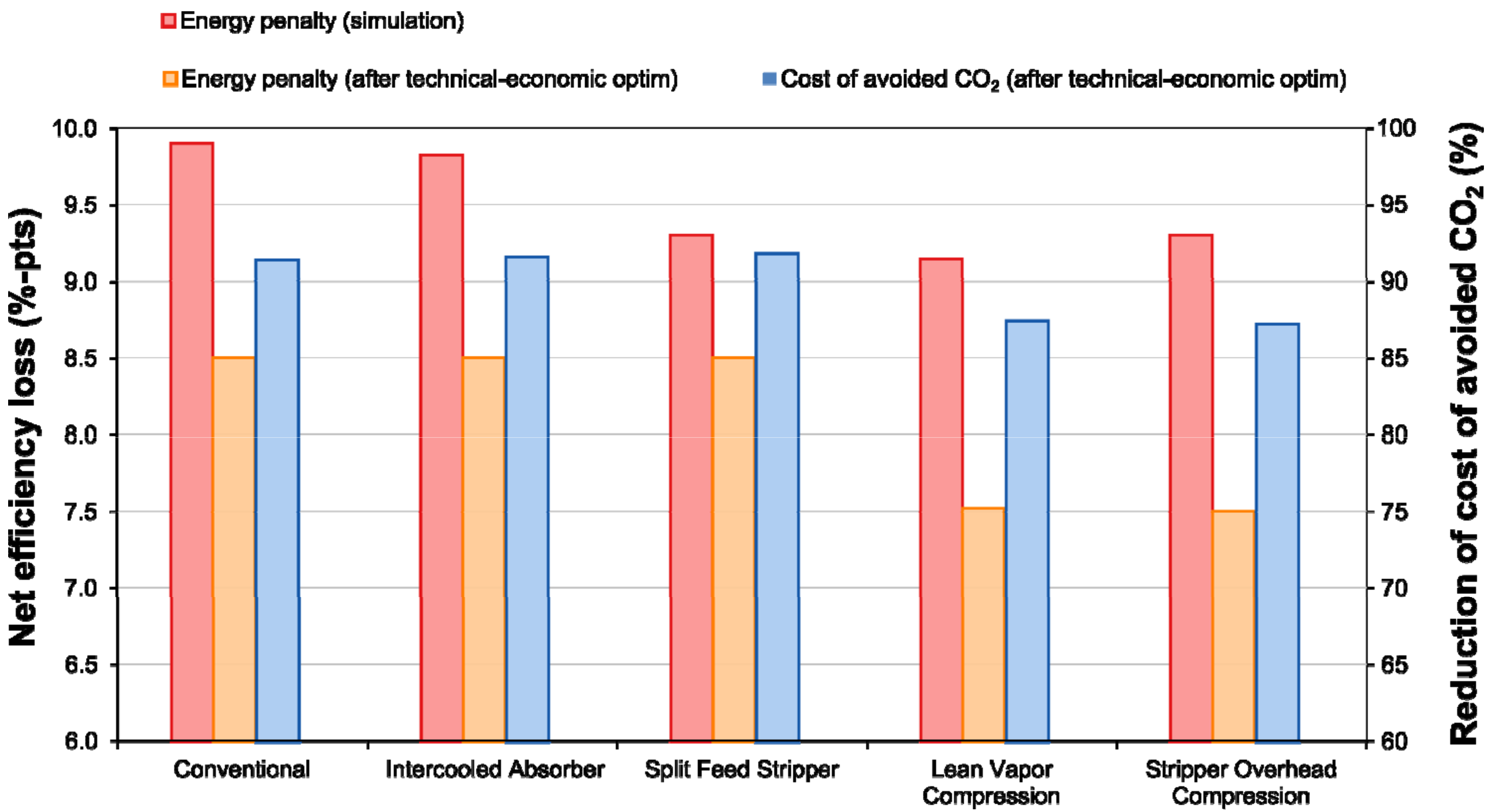
Influence of a 10% change of MEA properties on energy penalty and cost of avoided CO_2

MOST SENSITIVE PARAMETERS

Degradation ratio
for cost of avoided CO_2

CO_2 solubility
for energy penalty

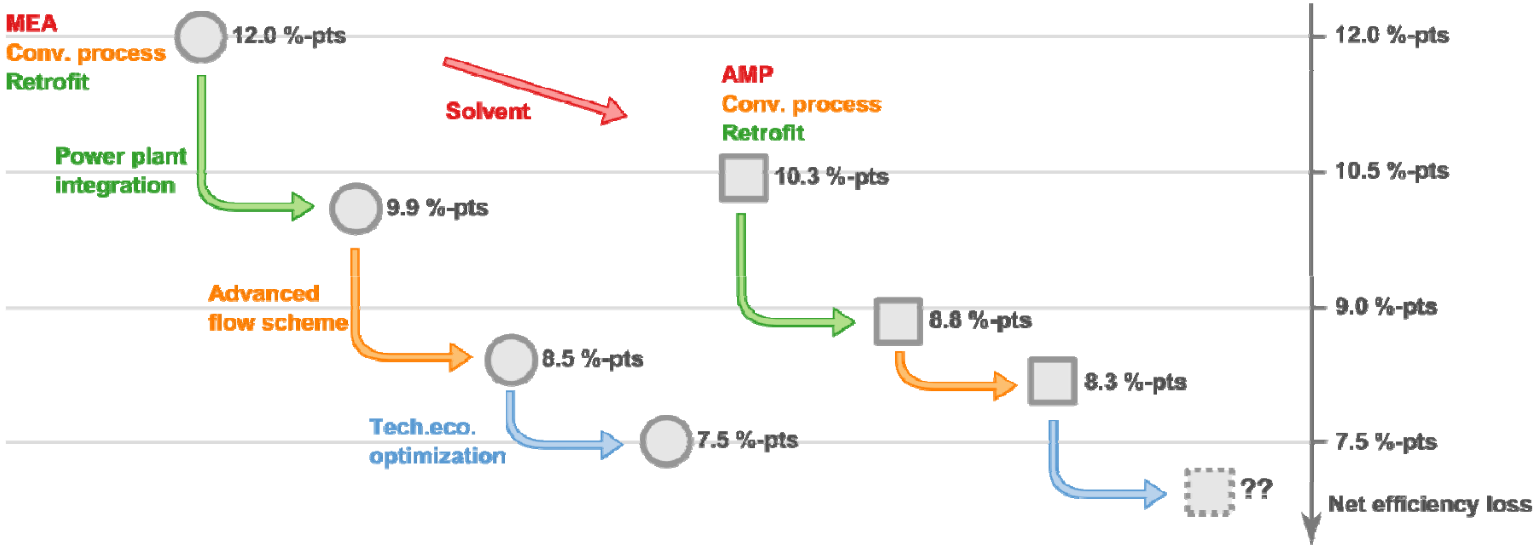
OPTIMIZATION RESULTS FOR MEA



SYNTHESIS

- **Three ways of performance improvement :** Solvent | Power plant integration | Process flow scheme

→ Need to consider **all** aspects in order to evaluate the potential of a solution



- **Perspectives**
  - Implement other fully characterized solvents
  - Evaluate advanced architecture by coupling process modifications with synergetic effects

A RELEVANT APPROACH

- **Technical-economic analysis**
  - **Coupled with a systematic optimization algorithm**
  - **Simultaneous resolution of design and operating parameters**

THANK YOU FOR YOUR ATTENTION !

Any questions?

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