Process engineering method for systematically comparing CO_2 capture options

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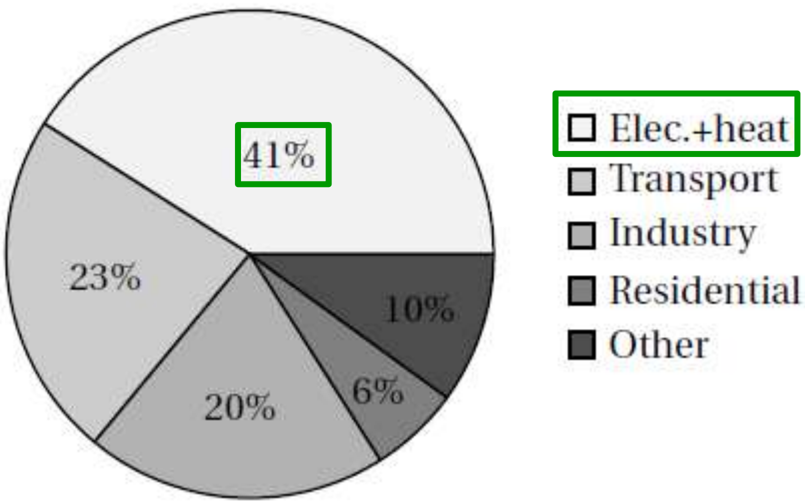
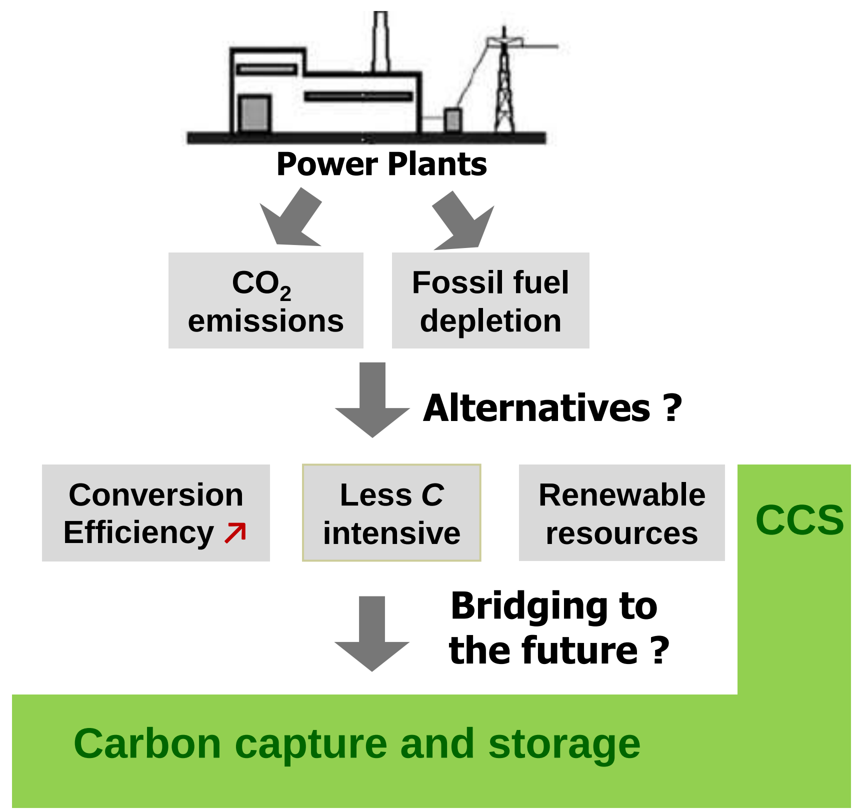
Context

- Dual global challenge
  - Greenhouse gas emissions ↘
  - Sustainable energy supply



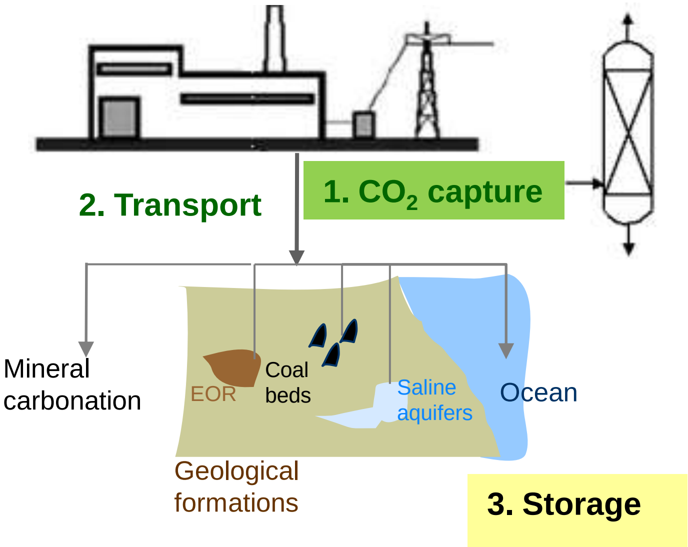
World CO_2 emissions from fuel combustion by sector in 2010 (IEA 2011)



Context

- CO_2 emissions ↘ & energy supply
  - Carbon capture and storage (CCS)[1]

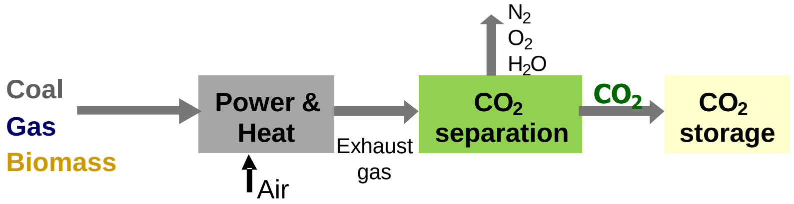
1. Capture
   - CO_2 removal from flue gas by gas separation technologies
2. Transport
   - CO_2 compression to 110bar
   - Transport by ship or pipeline
3. Storage
   - Geological formations
   - Ocean
   - Mineral carbonation



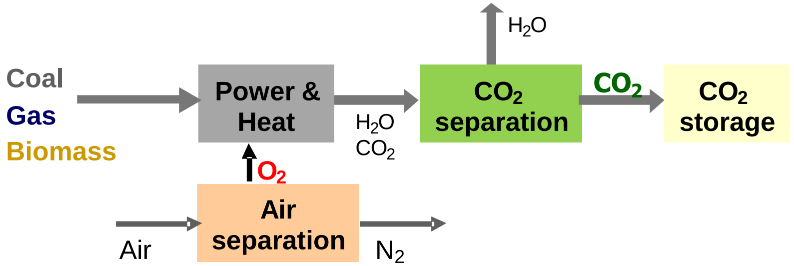
[1] IPCC Report 2005, ZEP Report 2011, IEA 2011

- CO_2 capture concepts

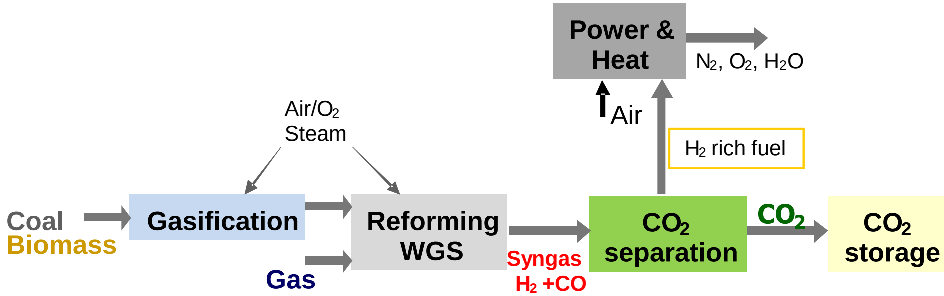
  - **Post-combustion**
    End of pipe CO_2 removal



  - **Oxy-fuel combustion**
    Pure O_2 combustion

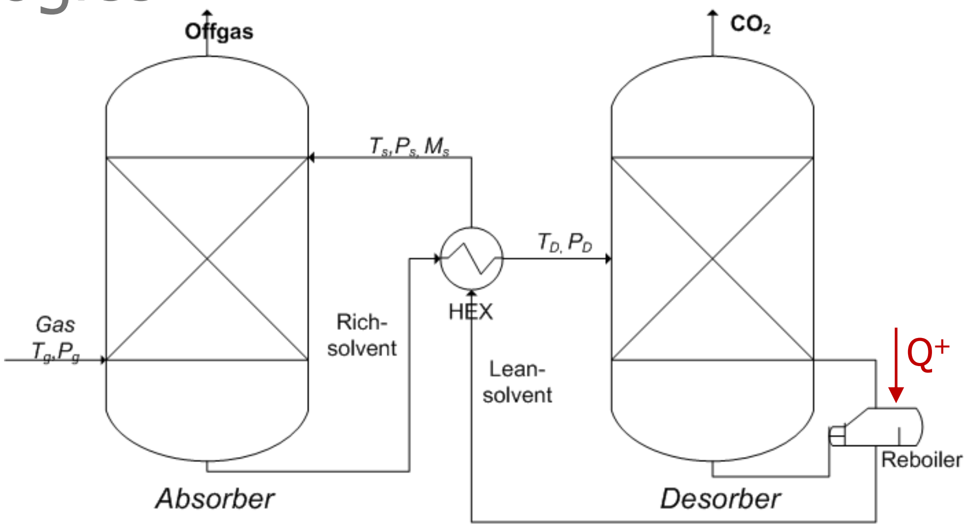


  - **Pre-combustion**
    Syngas intermediate, H_2 route



Context

- CO_2 separation technologies
  - Chemical absorption
  - Physical absorption
  - Physical adsorption
  - Membrane processes



Operating conditions ?

Separation/purification capacity ?

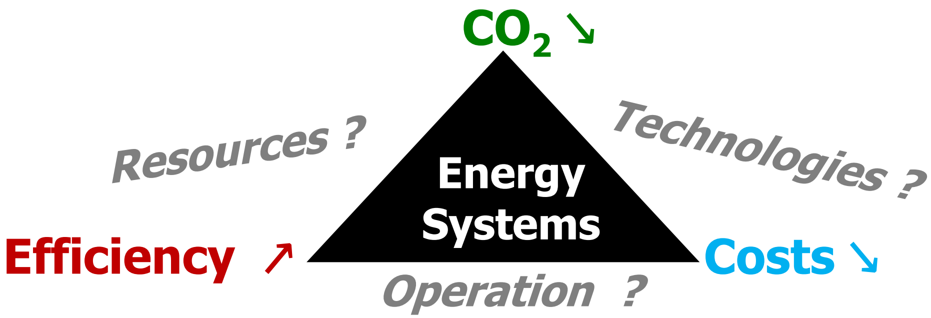
Energy requirement ?

Costs ?

Context

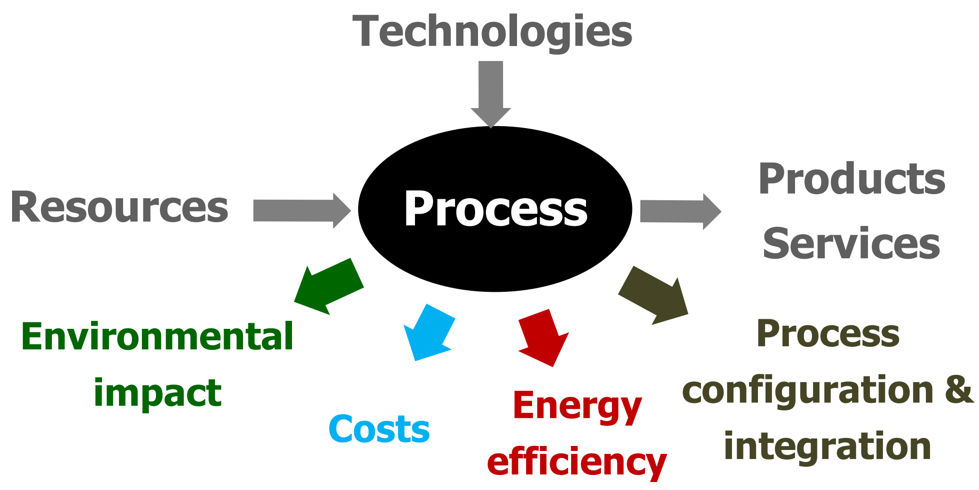
- Drawbacks of CO_2 capture & compression
  - Large energy requirement:
    - Up to **10%-pts efficiency penalty** (~2%-pts from CO_2 compression)
  - Additional investment:
    - **20-30% production cost increase**

- Challenge:
  - **Competitive** power plants **with CCS**



Objective

- Systematic optimisation of CO_2 capture processes
  - Thermo-environomic optimisation methodology[2]

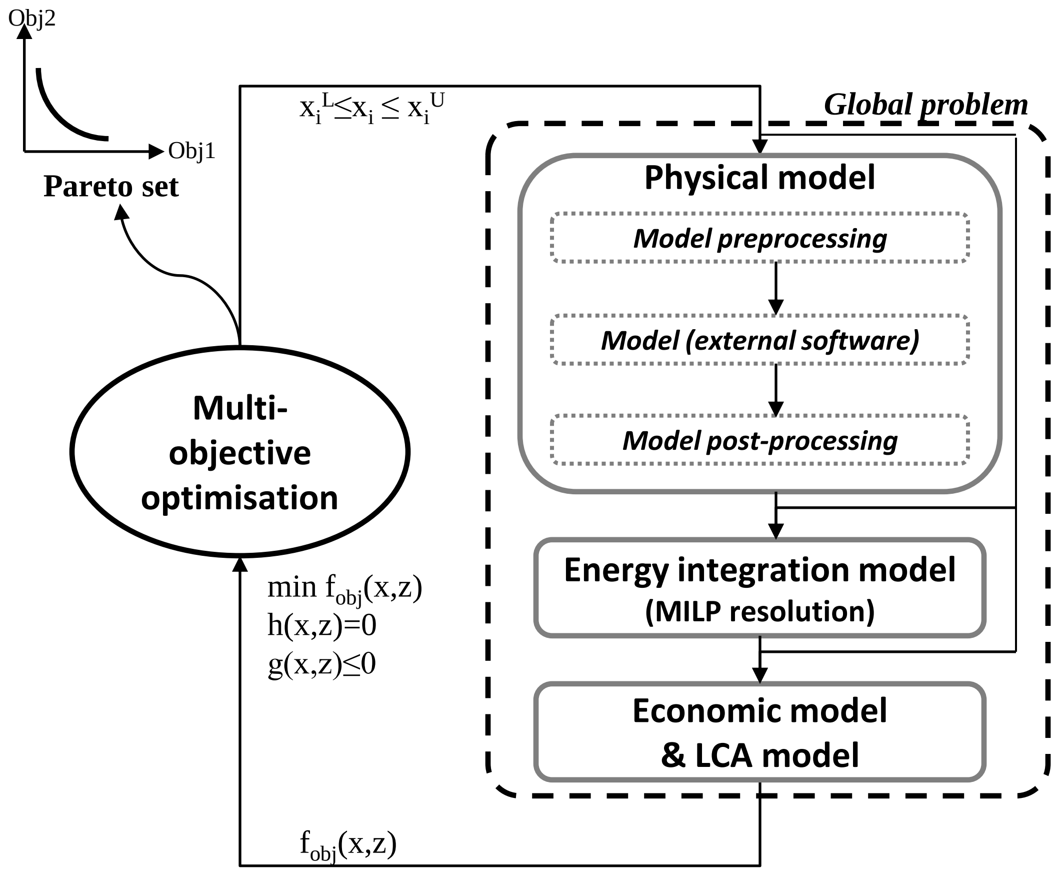


  - Thermodynamic, economic & environmental aspects
    - Trade-off between efficiency, costs and CO_2 capture rate!
    - Assessment of fuel decarbonisation competitiveness

[2] Gassner et al. 2009, Tock et al. PSE 2012

Methodology

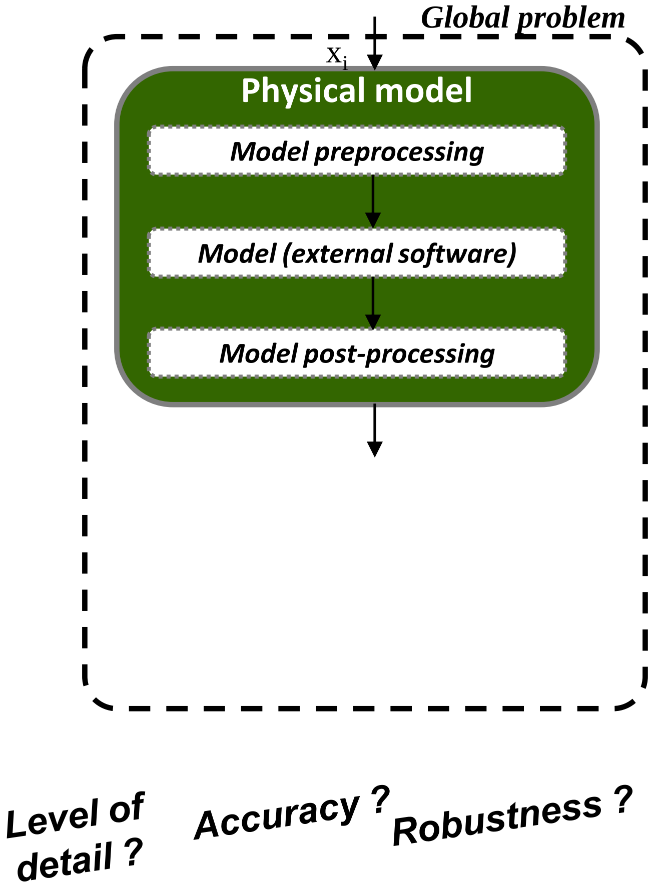
- Thermo-environomic optimisation methodology
  - Uniform and systematic platform[3]



[3]Tock et al. PSE 2012, Bolliger et al. 2009/2010, Gassner et al. 2009, Gerber et al. 2011

Methodology

- Process models



- Process units operation
  - Physical & chemical transformations
  - Heat transfer requirement

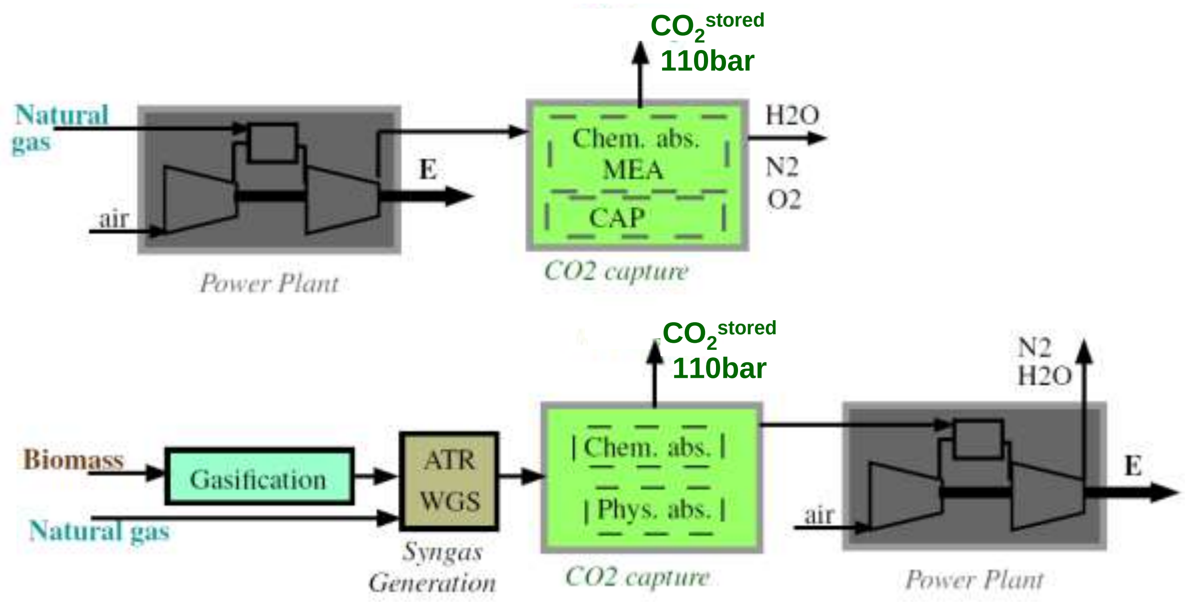
  - Coherent representation of existing technology
    - Accurate and flexible
    - Avoid needless complexity

Methodology

- Superstructure of candidate technologies
  - Conceptual process design of fuel decarbonisation

Post-combustion

Pre-combustion

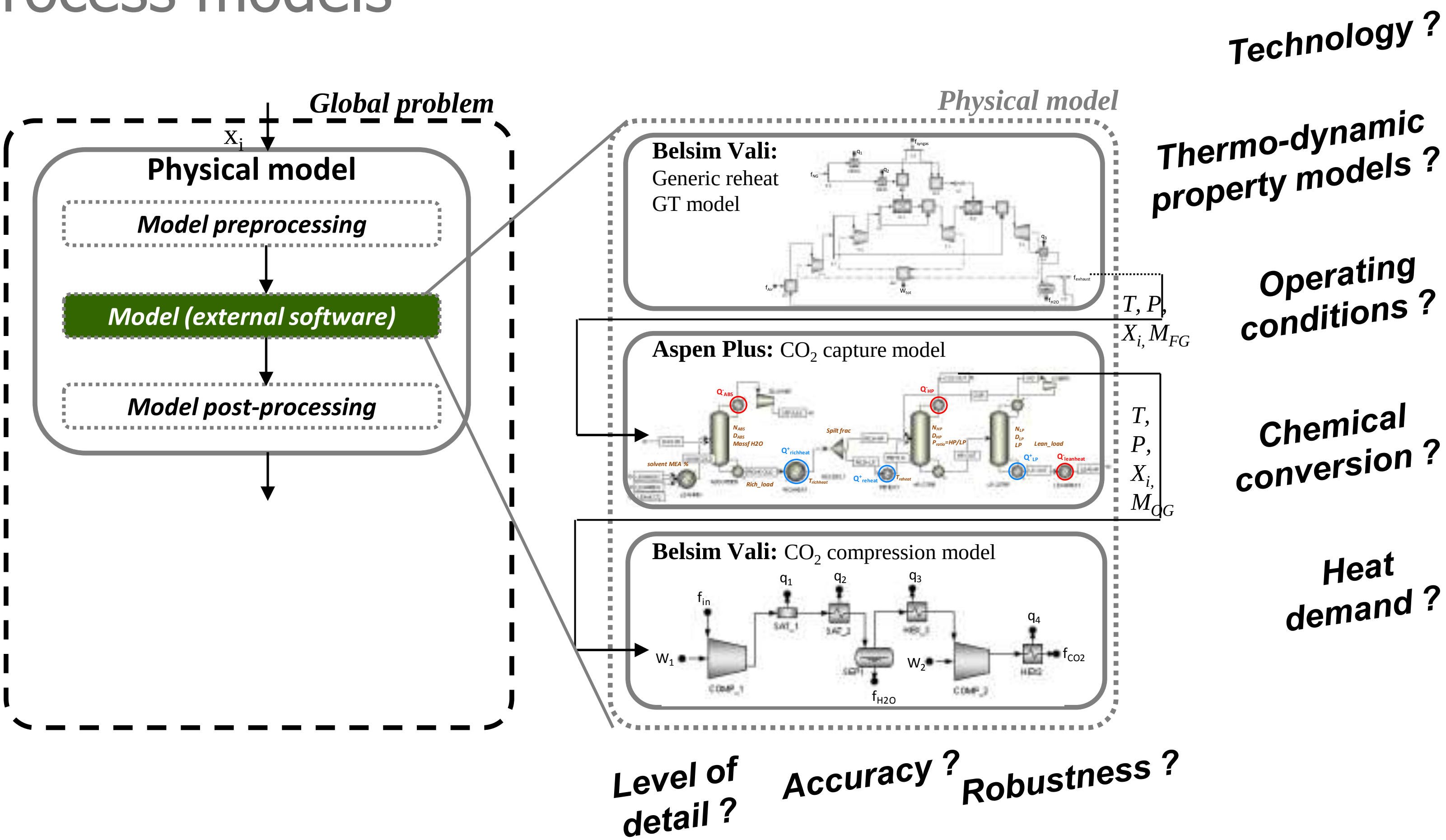


Process units ?

Process configuration ?

Decision variables ?

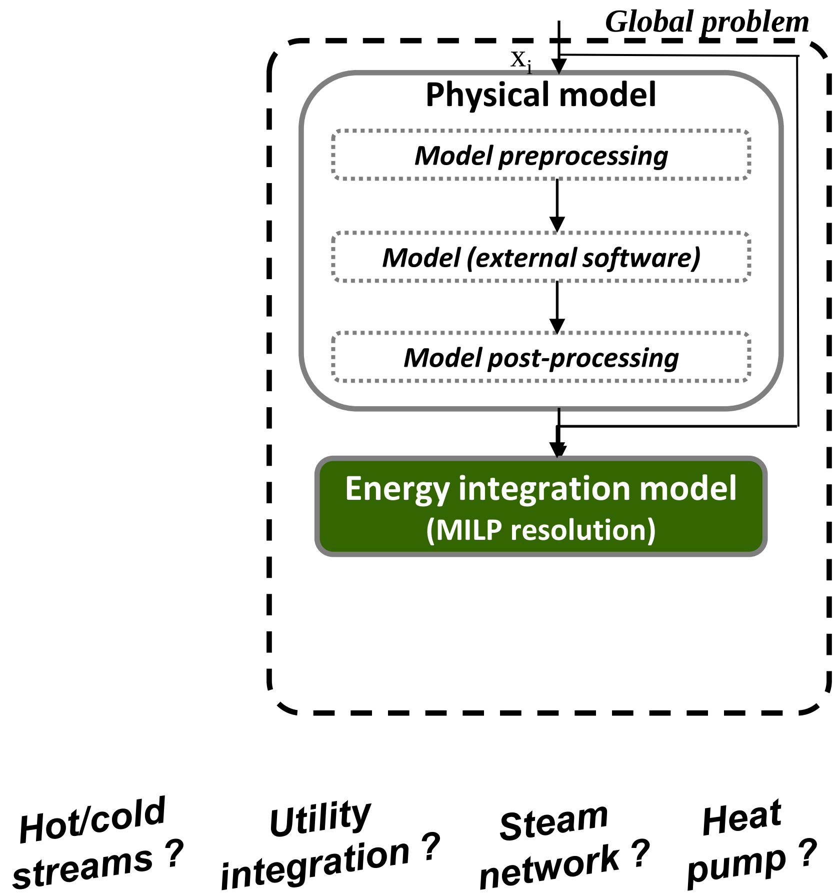
- Process models



- Process simulation:

  Connection between **different** flowsheeting **software !**

- Energy integration: Pinch analysis



- Optimal integration of process units
  - Maximal heat recovery[4]
  - Optimal combined heat & power production
    - Waste heat valorisation

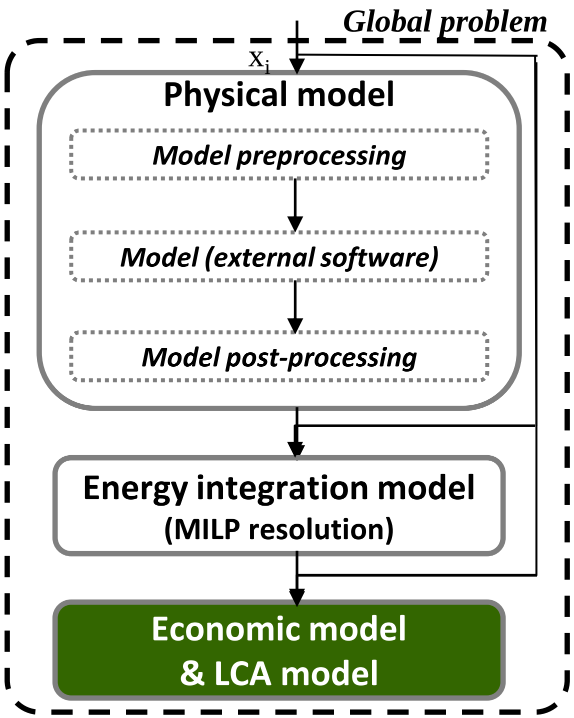
Potential improvements of process technology ?

- Resolution
  - Linear programming minimising operating cost

[4]Maréchal and Kalitventzeff 1998

Methodology

- Performance evaluation



Size ? **Material ?** **Operation ?** **Economic conditions ?**

- Economic performance[5]
  - Equipment sizing

$$size = f(T, P, \dot{m}, \dot{V}, ...)$$

  - Capital investment estimation

$$C_{GR} = f(T, P, material, size, ...)$$

  - Production costs

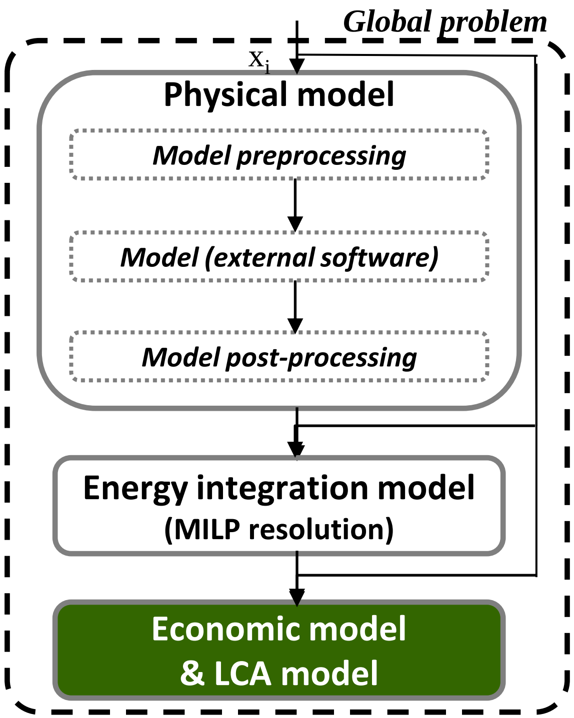
$$C_P = C_{I,d} + C_M + C_{OL} + C_{UT} + C_{RM}$$

Re-evaluation for different operation & plant size !

[5]Turton 2009, Ulrich 2003

Methodology

- Performance evaluation



Size ? *Material ?* *Operation ?* *Economic conditions ?*

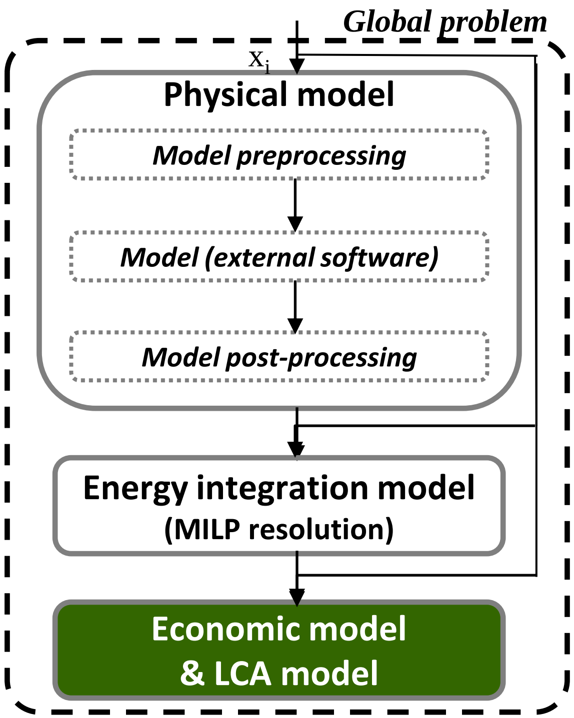
- Economic performance[5]
  - Uniform approach
  - Uniform assumptions

Parameter	Value
Marshall and Swift index	1473.3
Dollar exchange rate	1.2 $/€
Expected lifetime	25 years
Interest rate	6%
Yearly operation	7500h/y
Operators[a]	4p./shift
Operator's salary	91'070 $ /y
Wood price (θ_{wood}=50%wt)	13.9 $ /GJ_{BM}
Electricity price (green)	75 $ /GJ_e
MEA price	0.970 $/$kg_{MEA}$
Natural gas price	9.7 $/$GJ_{NG}$

[5]Turton 2009, Ulrich 2003

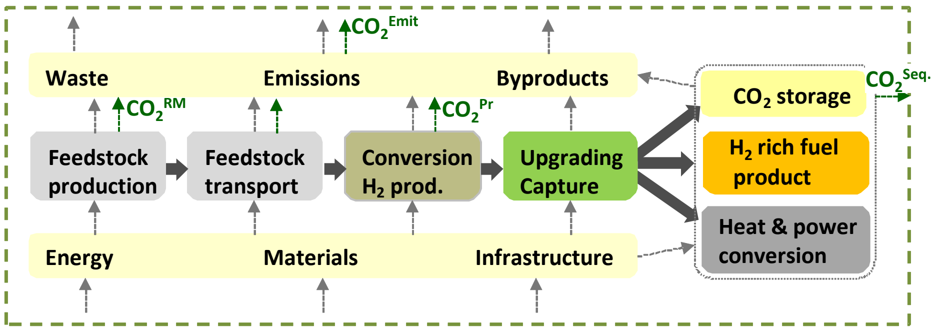
Methodology

- Performance evaluation



- Environmental impacts[6]
  - Life cycle assessment (LCA)

    Life cycle inventory considering specific operating conditions



System boundary ?

Functional unit ?

Impact method ?

Contributions ?

Global warming potential ?

Resources depletion ?

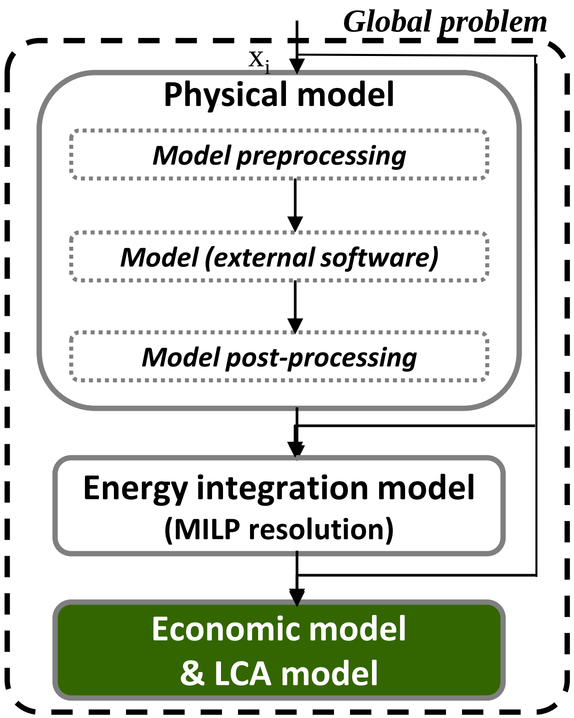
Ecosystem ?

CO_2 capture benefit ?

Biomass versus natural gas ?

[6]Gerber et al. 2011

- Performance evaluation



Thermo-dynamic ? Economic ? Environmental ?

- Performance indicators
  identify optimal process design
  - Energy efficiency

$$\varepsilon_{tot} = \frac{\Delta h^0_{fuel,out} \cdot \dot{m}^-_{fuel} + \dot{E}^-}{\Delta h^0_{feed} \cdot \dot{m}^+_{feed} + \dot{E}^+}$$

  - CO_2 capture rate

$$CO_2 \text{ capture } [\%] = \frac{\dot{n}_{C_{captured}}}{\dot{n}_{C_{in}}} \cdot 100$$

  - CO_2 avoidance costs

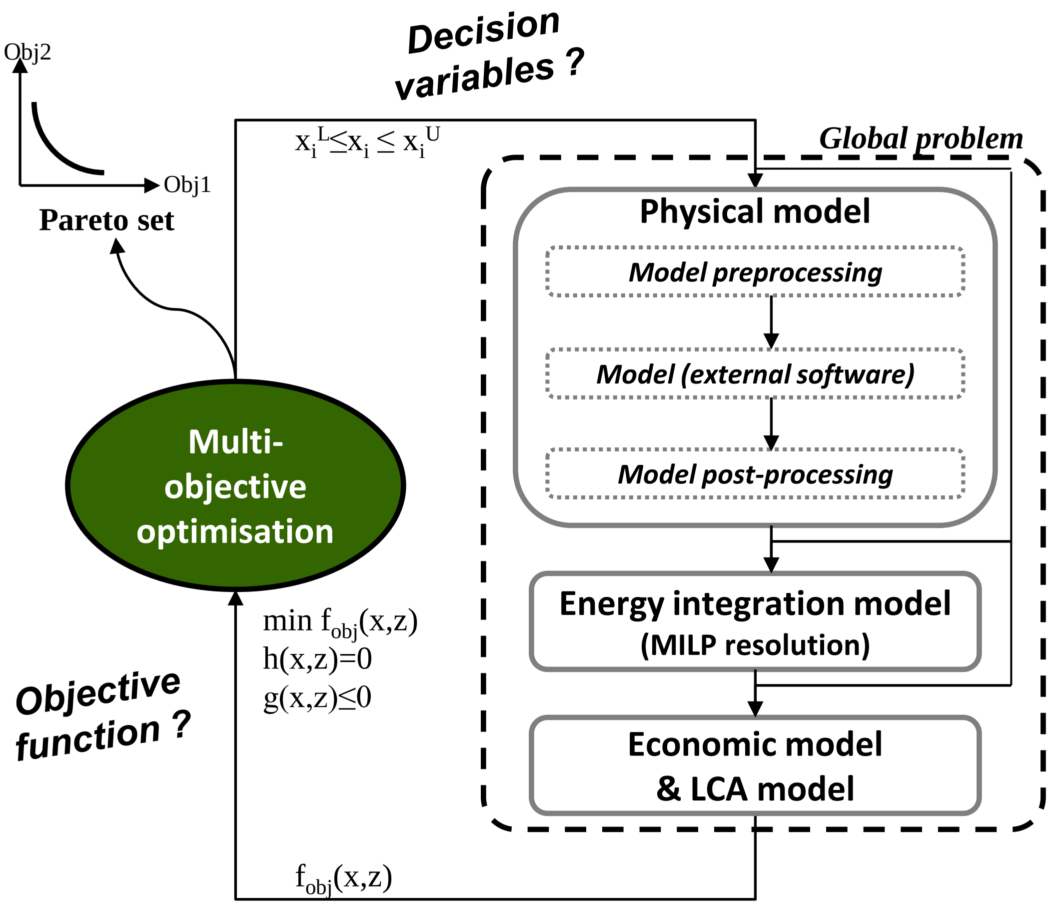
$$\$/t_{CO2,avoided} = \frac{C_{Pcc} - C_{Pref}}{\dot{m}_{CO_2\ emit,ref} - \dot{m}_{CO_2\ emit,CC}}$$

➡ *Competing indicators*

Trade-offs assessment !

Methodology

- Multi-objective optimisation



- MINL problem[7]
  - Evolutionary algorithm
  - Optimal values of decision variables
  - Pareto optimal frontier

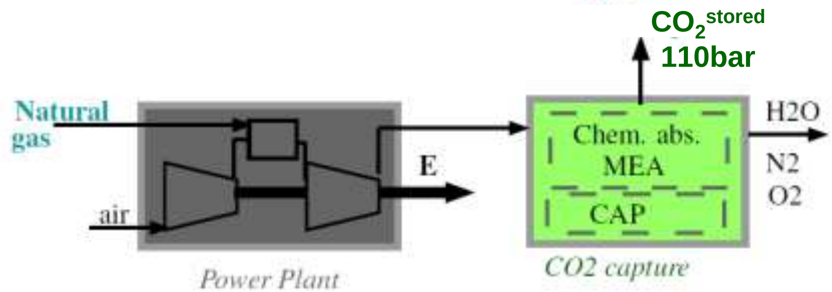
Trade-offs ?

Decision-making ?

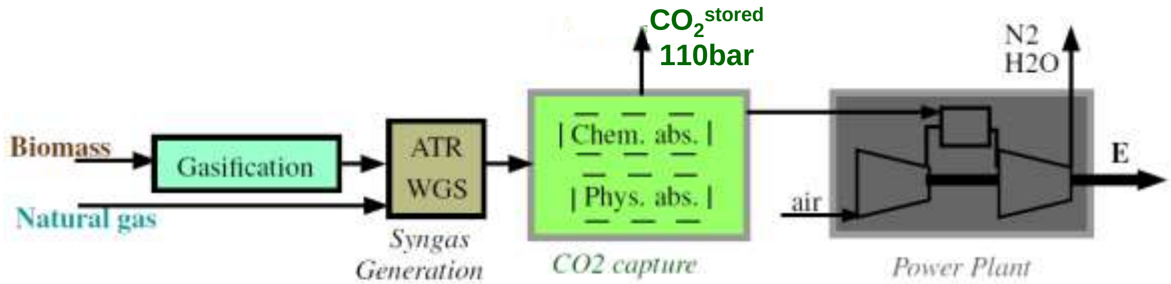
[7]Molyneaux et al. 2010

CO_2 capture optimisation

Post-combustion



Pre-combustion

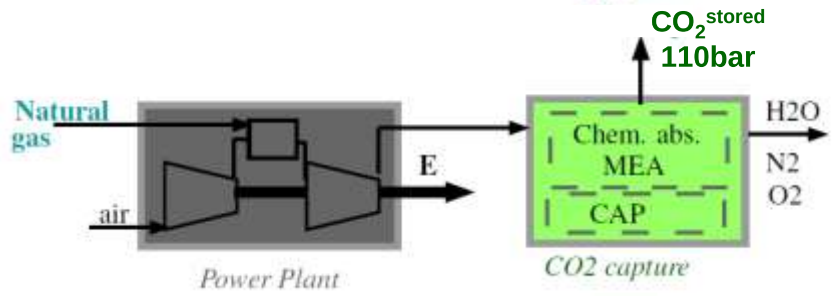


- Detailed modelling
  - Chemical absorption
  - Physical absorption

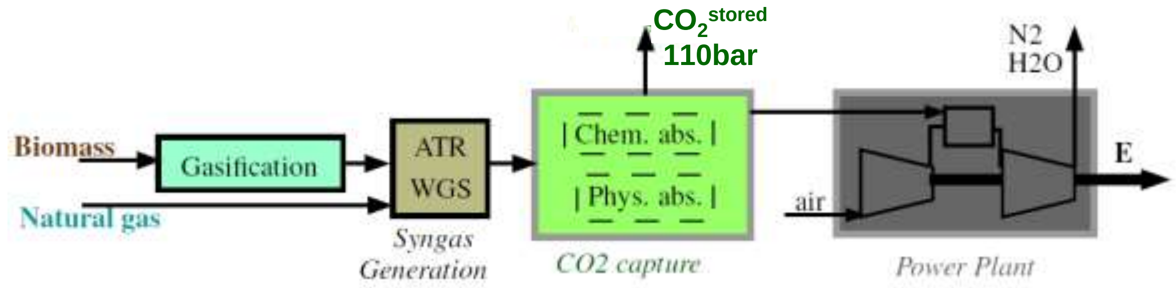
- Decision variables
  - Operating conditions (T, P, S/C,…), cogeneration system

CO_2 capture optimisation

Post-combustion



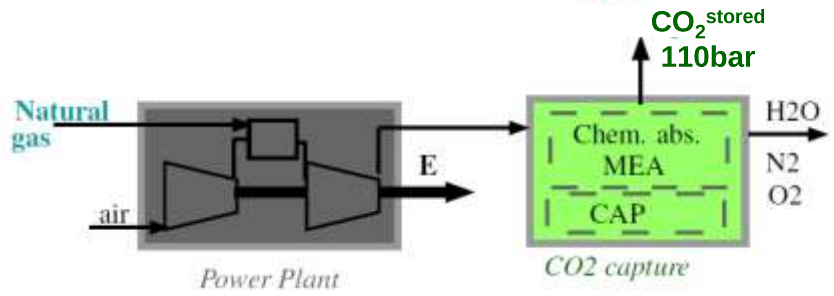
Pre-combustion



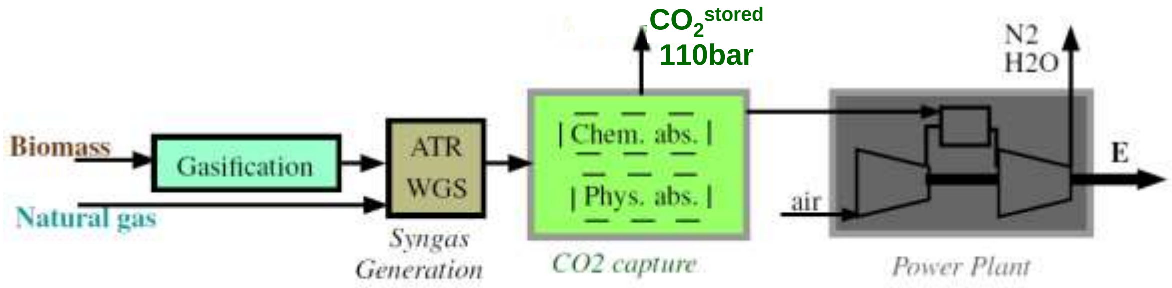
- Multi-criteria comparison
  - Thermo-dynamic
  - Environmental
  - Economic
    - Sensitivity to resource price, carbon tax, etc.

CO_2 capture optimisation

Post-combustion



Pre-combustion



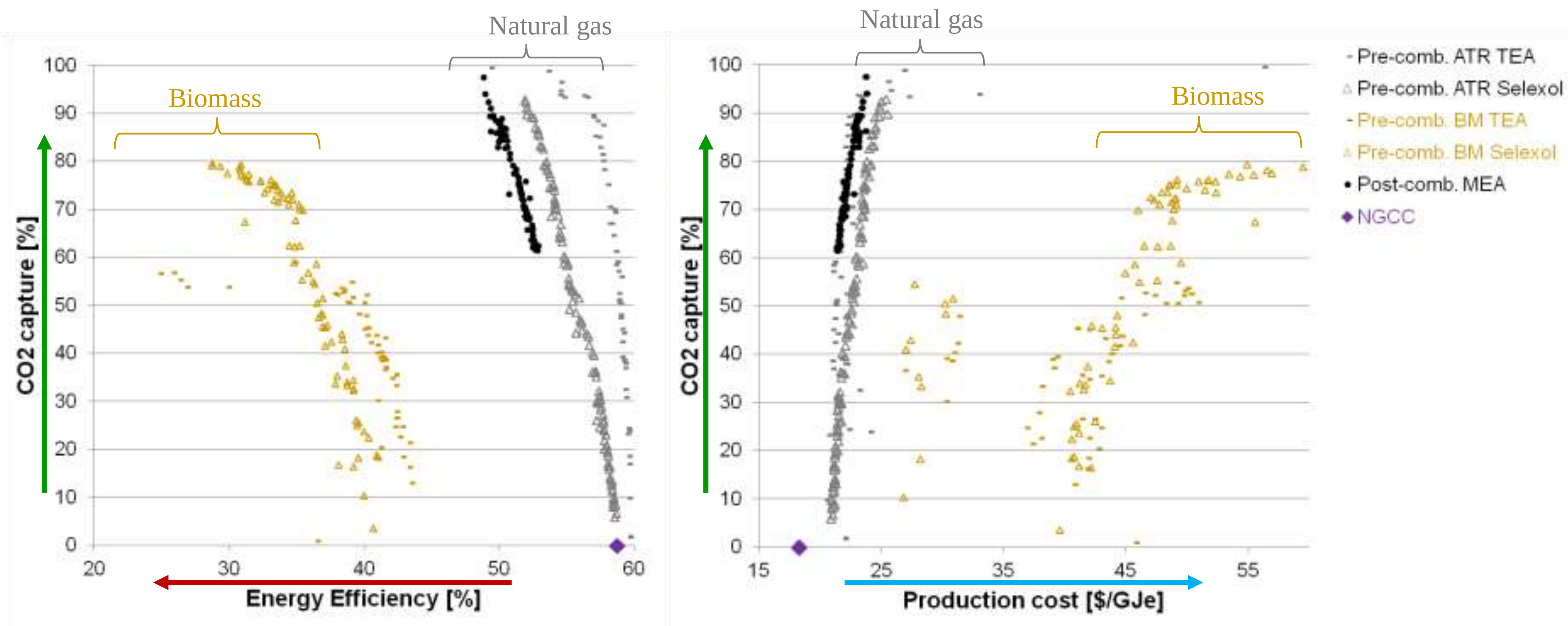
- Multi-objective optimisation
  - Maximisation of energy efficiency
  - Maximisation of CO_2 capture rate

$$\varepsilon_{tot} = \frac{\Delta h^0_{fuel,out} \cdot \dot{m}^-_{fuel} + \dot{E}^-}{\Delta h^0_{feed} \cdot \dot{m}^+_{feed} + \dot{E}^+}$$

$$CO_2 \text{ capture } [\%] = \frac{\dot{n}_{C_{captured}}}{\dot{n}_{C_{in}}} \cdot 100$$

CO_2 capture optimisation

- Pareto-optimal frontiers



➢ CO_2 capture ↗ → ε_{tot} ↘ & COE ↗

Energy & cost penalty of CO_2 capture and compression

Economic scenario base: 9.7\$/GJ_{res}, 7500h/y, 25y, 6%ir

CO_2 capture options comparison

- CO_2 capture energy and cost penalty
  - Different process configurations
    - Natural gas fed processes 90% CO_2 capture, biomass 60% capture

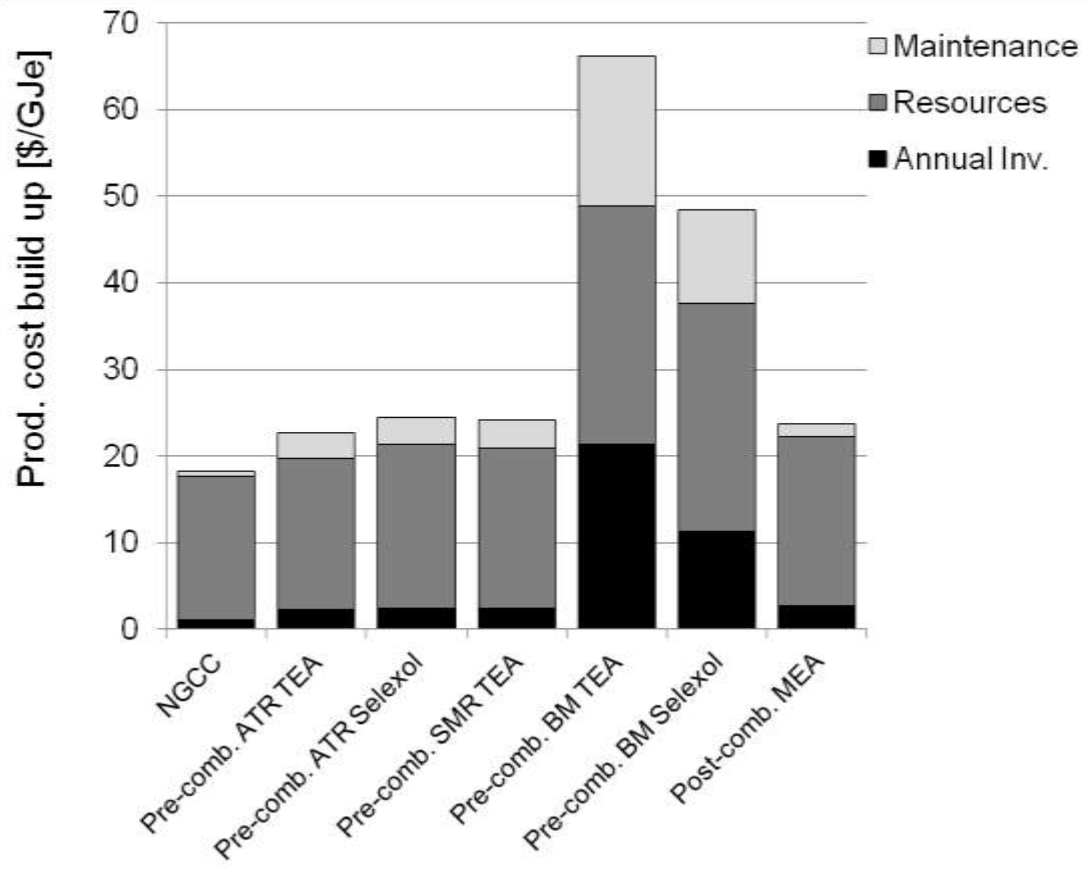
System	NGCC no CC	Post-comb MEA	ATR TEA	ATR Selexol	SMR TEA	BM TEA	BM Selexol
Feed [MW_{th}]	559	587	725	725	725	380	380
CO_2 capture [%]	0	89.5	89.7	89.1	89.3	59	59
ε_{tot} [%]	58.75	49.6	56.8	52.6	53.3	34.8	34.8
Net electricity [MW_e]	333	296	412	381	386	132	132
Power steam network [MW_e]	113.4	101	82.5	67.7	55.6	45.7	45.7
Power GT [MW_e]	219.5	227	368	369	350	132	132
COE [$/$GJ_e$]	18.31	23.17	22.67	24.5	24.1	66.1	49.5
Annual Invest. [$/$GJ_e$]	1.1	2.1	2.2	2.4	2.3	21.4	11.2
Avoidance cost [$/$t_{CO2,avoid}$]	-	53.8	45.8	66	61.9	173.6	113.3
CO_2 emissions [kg_{CO2}/GJ_e]	105	14.9	10.1	11.5	11.2	-170.4	-170.4
IPCC GWP [$kg_{CO2,eq}/GJ_e$]	120	34	30	31.9	36.1	-139.6	-134.2
EI99 [pts/GJ_e]	7.48	7.7	7.7	8.1	9.0	6.2	6.1
EI99 Resources Contr.[%]	78.41	89.22	82.35	83.36	79.49	17.44	17.23
EI99 Health Contr.[%]	19.30	9.25	13.67	13.36	14.95	6.65	6.95
EI99 Ecosystem Contr.[%]	2.29	1.53	3.99	3.28	5.56	75.92	75.82

  - Competition between post- and pre-combustion

Economic scenario base: 9.7$/$GJ_{res}$, 7500h/y, 25y, 6%ir

CO_2 capture options comparison

- CO_2 capture energy and cost penalty



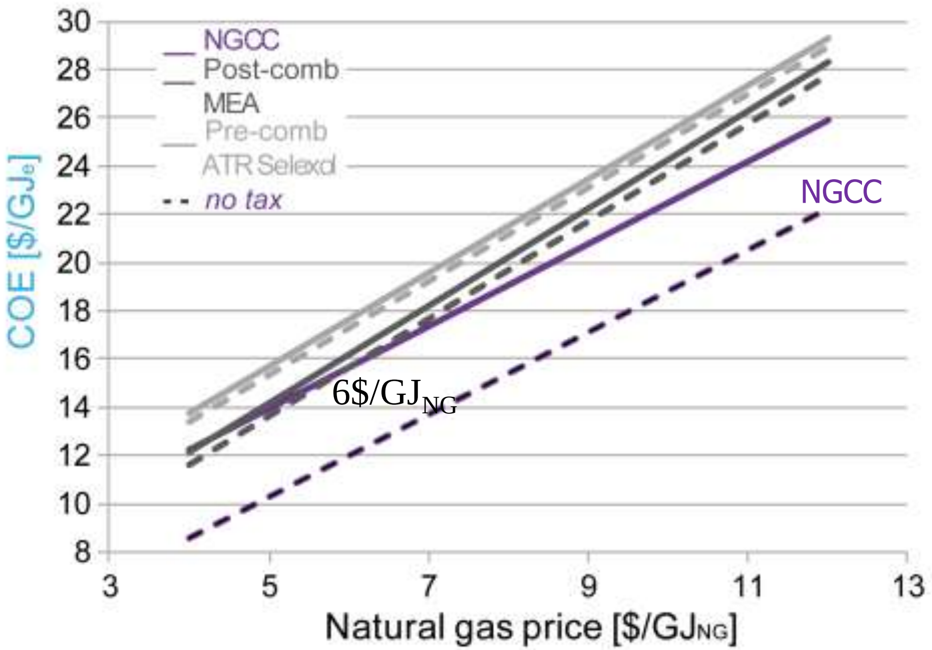
- Economic competitiveness highly influenced by
  - Resource price & carbon tax

Economic scenario base: 9.7$/GJ$_{res}$, 7500h/y, 25y, 6%ir

CO_2 capture options comparison

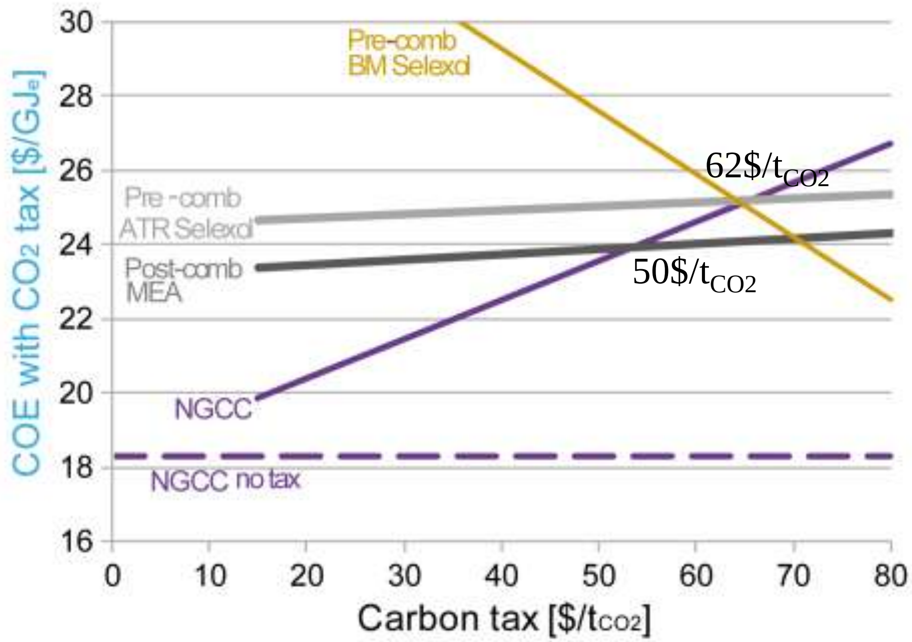
- Economic conditions sensitivity analyses
  - Natural gas price influence

    Carbon tax 35$/$t_{CO2}$



  - Carbon tax influence

    Resource price 9.7$/$GJ_{NG}$, 5$/GJ_{BM}

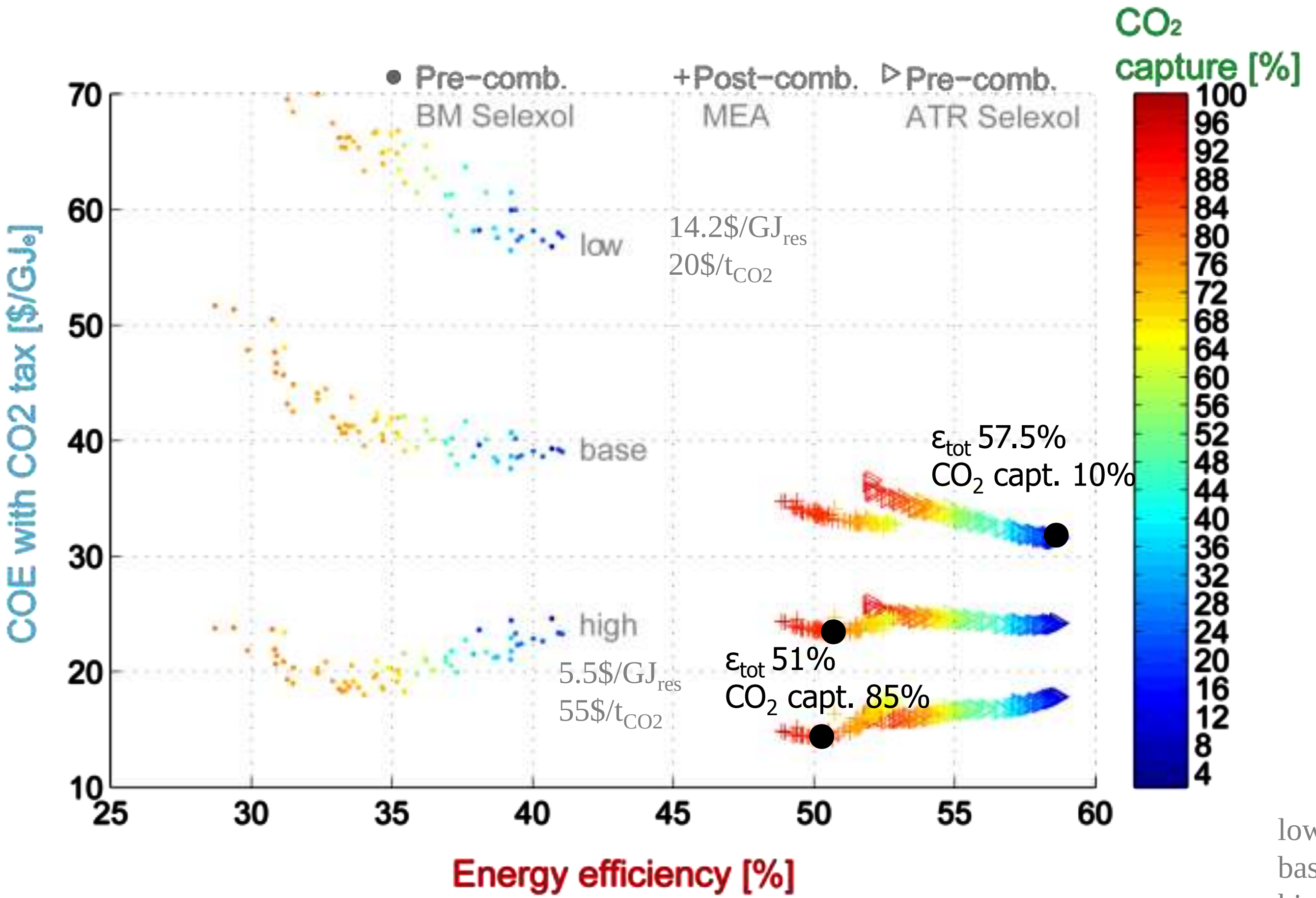


  - COE strongly dependent on resource price!
  - With increasing carbon tax CO_2 capture becomes competitive!

Economic scenario base: 9.7$/$GJ_{res}$, 7500h/y, 25y, 6%ir

CO_2 capture options comparison

- Economic competitiveness of process configurations
  - Influenced by economic conditions



- Optimal process design ?

low: 14.2$/$GJ_{res}$, 20$/t_{CO2}, 4500h/y, 15y, 4%ir
base: 9.7$/$GJ_{res}$, 35$/t_{CO2}, 7500h/y, 25y, 6%ir
high: 5.5$/$GJ_{res}$, 55$/t_{CO2}, 8200h/y, 30y, 8%ir

CO_2 capture options comparison

- Most economically competitive process configurations

System	NGCC	Post-comb	ATR	BM
Performance	**no CC**	**MEA**	**Selexol**	**Selexol**
Feed [MW_{th}]	559	582	725	380
CO_2 capture [%]	0	82.9	78.6	69.9
ε_{tot} [%]	58.75	50.6	**53.5**	35.4
Net electricity [MW_e]	328	295	383	135
[$kg_{CO2, local}/GJ_e$]	105	13.9	22.2	**-198.1**
COE incl. tax[$/$GJ_e$]	18.2-28.8	**9-40**	12.8-42	15-69
Avoid. Costs incl. tax [$/$t_{CO2,avoided}$]	-	-63-121	-49-127	0-253

- CO_2 capture penalty
  - *Efficiency* ↘: 6-10%-pts (CO_2 compression ~2%-pts)
  - *COE* ↗: 20-25%
- Best performing process
  - *Efficiency:* Nat gas. pre-comb.
  - *Economic:* Nat gas. post-comb.
  - *Environmental:* Biomass pre-comb.
- Competition between processes and objectives!

Decision-making

- Most economically competitive process configurations

System Performance	NGCC no CC	Post-comb MEA	ATR Selexol	BM Selexol
Feed [MW_{th}]	559	582	725	380
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- CO_2 capture penalty
  - *Efficiency* ↘: 6-10%-pts (CO$_2$ compression ~2%-pts)
  - *COE* ↗: 20-25%
- Best performing process
  - *Efficiency*: Nat gas. pre-comb.
  - *Economic*: Nat gas. post-comb.
  - *Environmental*: Biomass pre-comb.

- Choice of optimal process configuration is defined by **production scope** and priorities given to the different **thermo-environomic criteria**!

Conclusions

- Quantitative & consistent evaluation of CO_2 capture
  - Systematic methodology for the thermo-environomic comparison and optimisation
    - Flowsheeting
    - Energy integration
    - Performance evaluation (efficiency, cost, LCIA)
    - Multi-objective optimisation
  - Powerful tool to assess process competitiveness

Conclusions

- Energy & cost penalty of CO_2 capture
  - Efficiency ↘: 6-10%-pts
  - COE ↗: 20-25%
  - COE with carbon tax → competitive

  - Competition between the different processes!
    - **Post-combustion CO_2 capture** in NGCC plants yields best *economic performance* for 70-85% capture
    - **Pre-combustion CO_2 capture** in natural gas fired power plants highest *energy efficiency*
    - CO_2 capture in **biomass based power plants** lowest *environmental impacts*

➡ *Competitiveness on energy market depends strongly on resource price, imposed CO_2 taxes and technologies!*

Thank you
for your attention!

Publications

- Tock L. , *Thermo-environomic optimisation of fuel decarbonisation alternative processes for hydrogen and power production,* PhD Thesis N°5655, EPFL, Lausanne, 2013
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