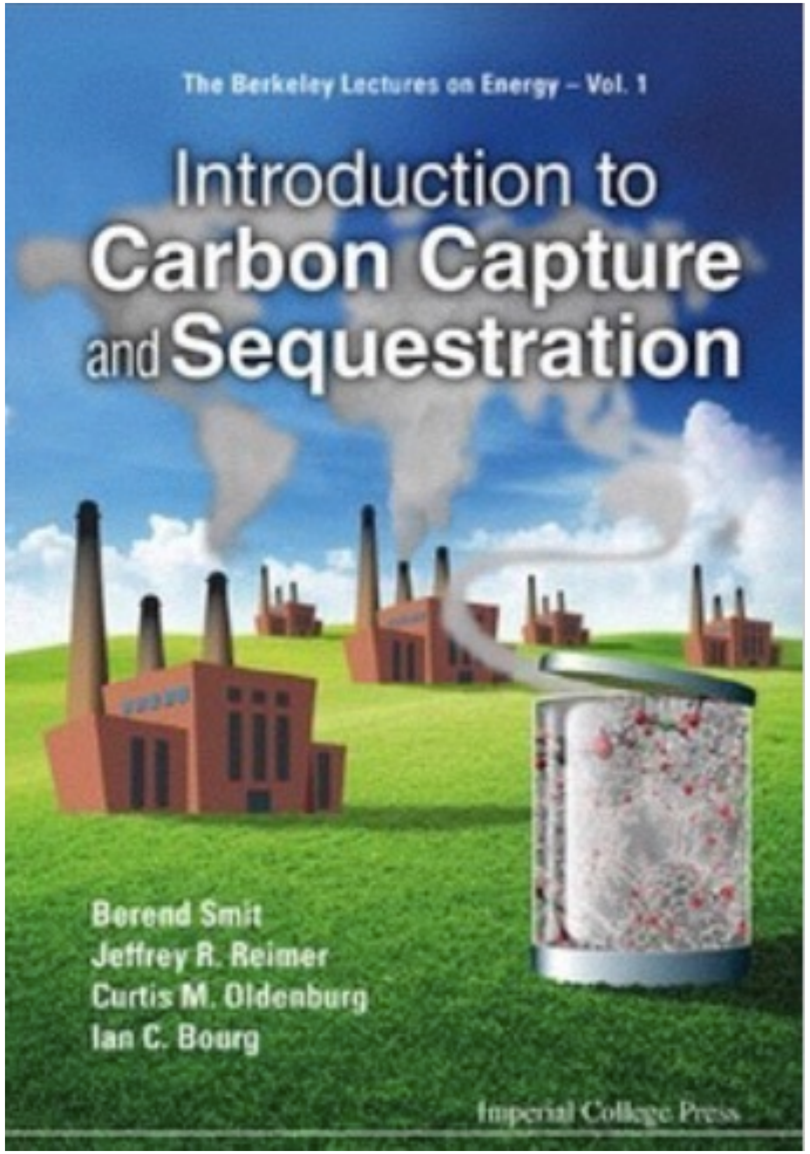
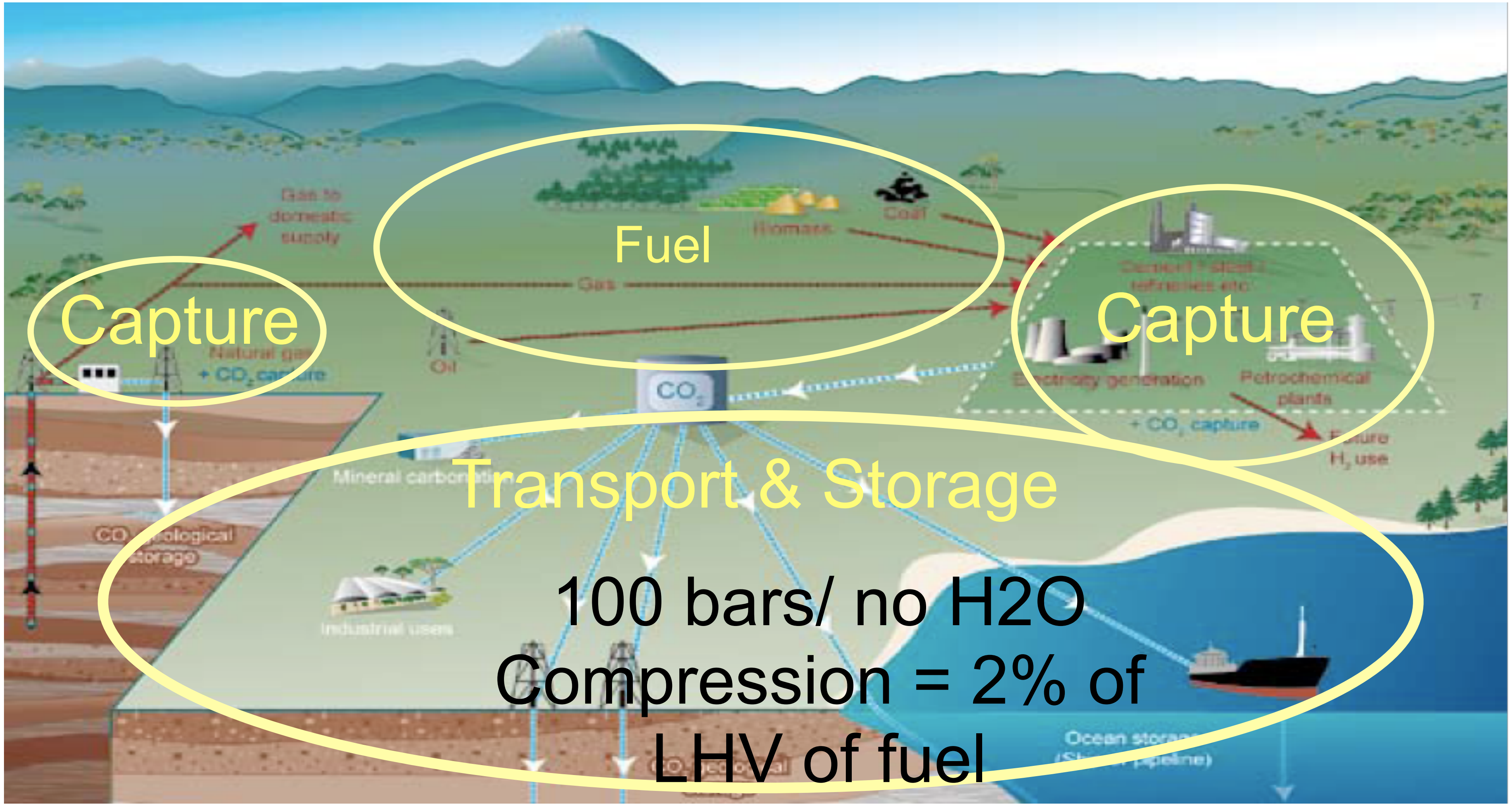
CO2 Capture, Sequestration and Re-Use

Prof. François Marechal

Further readings



CO_2 capture and storage (CCS)



(source : IPCC CCS Report)

CO2 capture in power plants

CxHy + (x+y/4)O2 + (x+y/4) 3.77 N2 => **xCO2** + y/2 H2O + (x+y/2) 3.77 N2

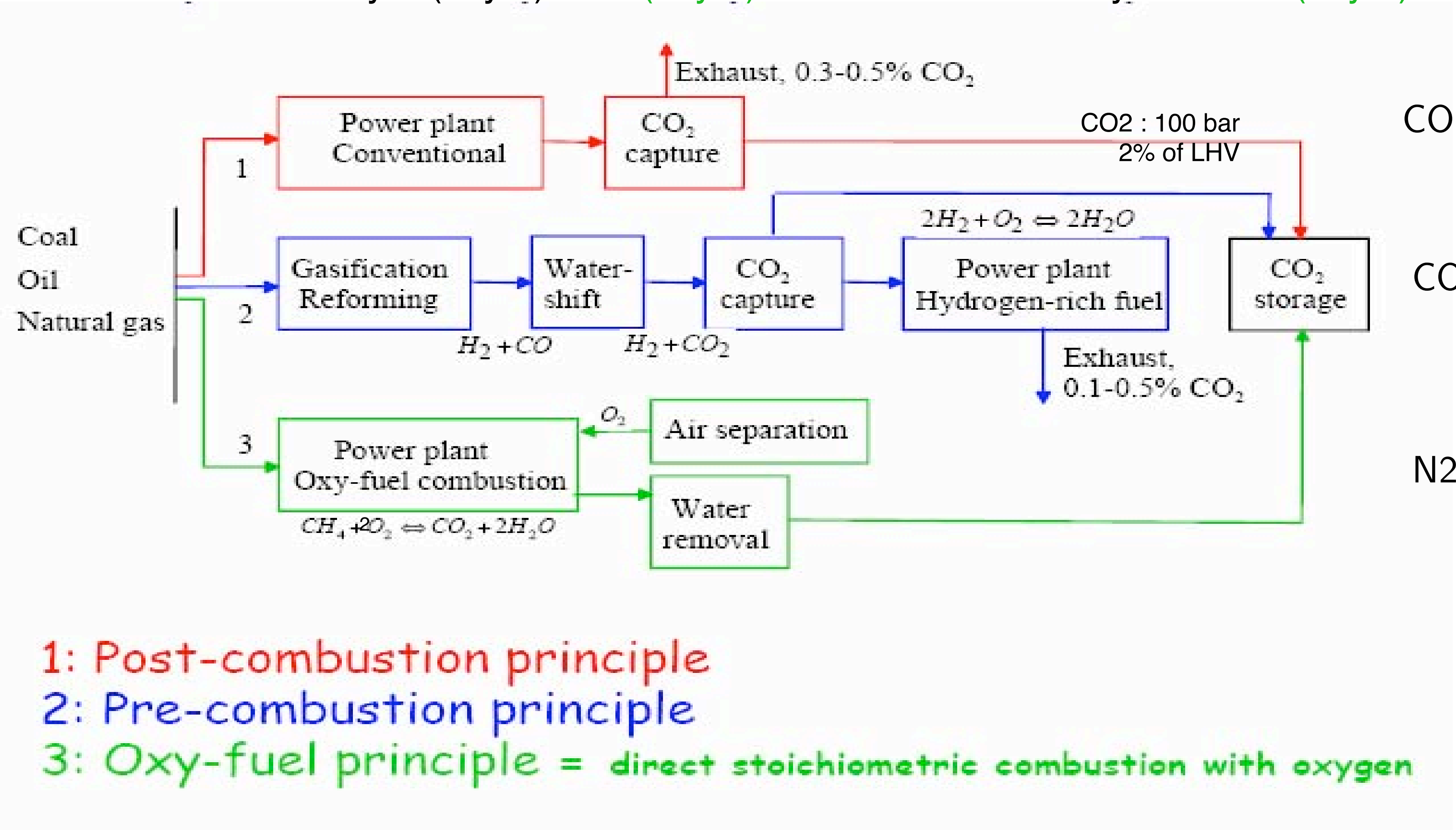


Fig. 3.17 Options for CO_2 separation [16]

CO2 separated from flue gases
CO2/N2

CO2 separated from Fuel
CO2/H2

N2 avoided in flue gases

[16] O. Bolland, Options for oxy-fuels & pre-combustion decarbonisation cycles (ALSTOM POWER). 2002, Norwegian University of Science and Technology Department of Energy and Process Engineering . Presentation for Alstom Cross Segment CO2 Mitigation Group October 11th 2002.

Ab(d)sorption systems

- Absorbent : reversible CO2 chemical reaction with a solvent
- Adsorbent : reversible CO2 physical reaction with a solvent
- Temperature and pressure conditions
- CO2 delivery conditions for transport and sequestration

Table 1: Comparison of physical and chemical ab- and adsorption for CO_2 separation [13].

Process	Conditions	Gas removed	Thermal Energy kWh/kgCO_2	Mechanical work kWh/kgCO_2	CO_2 purity %
Rectisol	$T_{abs} \approx -10/-70°C$ p_{CO2}>10bar	CO_2 , NH_3 H_2S, COS, HCN	0.025	0.038	<90%
Selexol	p_{CO2}≈7-30bar	CO_2 , NH_3 H_2S, COS, HCN	0.016-0.024	0.03-0.06	
MEA	$T_{abs} \approx 40°C$, 1-5bar $T_{desorb} = 95-120°C$	CO_2 ,CS_2 H_2S, SO_2, COS	2.3	0.05-0.3	< 99%
PSA-Flue gas 28-34% CO_2	$P_{ad} = 1bar$, $P_{desorb} = 0.05-0.9bar$	CO_2	0.16-0.18		
PSA - syngas	$P_{ad} = 13-21bar$, $P_{desorb} < 1bar$	CO_2			>90%

N2,O2 + CO2<< (90% captured)

CO2>> to sequestration

needs compression to 100 bar=2% of heating value!

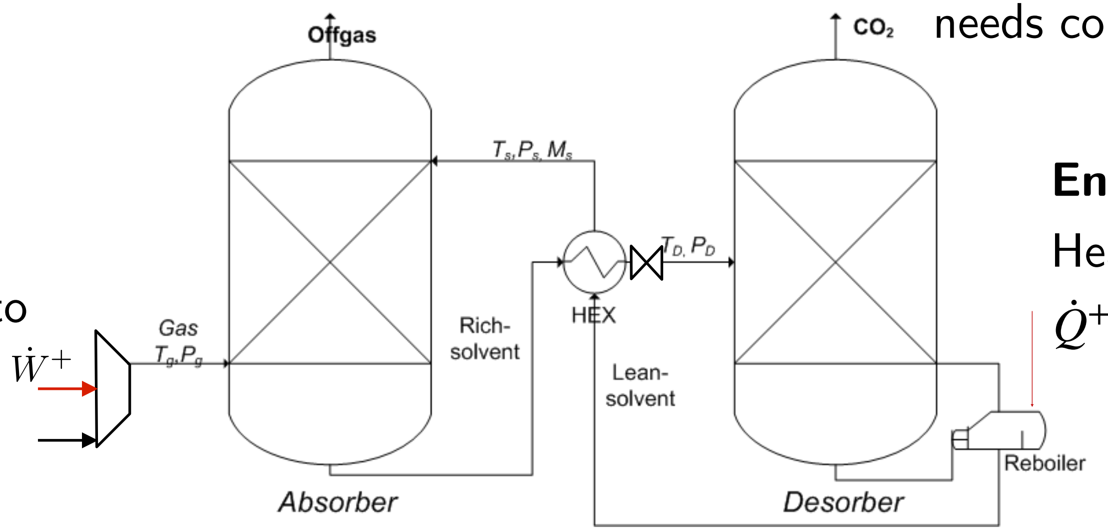
Capital cost :

Size depends on CO2 partial pressure and flow

Energy cost :

Compression flue gases to operating pressure

CO2,N2,O2



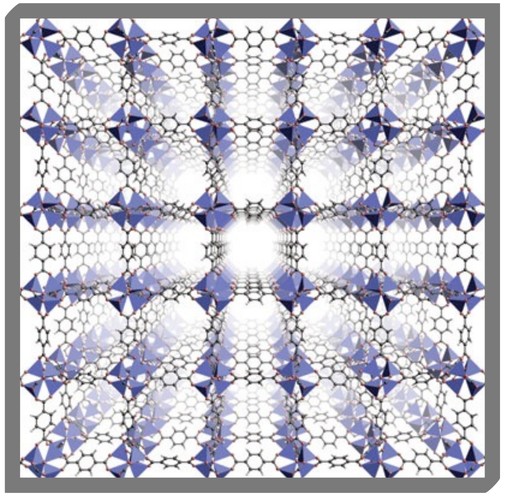
Energy cost :

Heat of desorption (MJ/kg CO2)

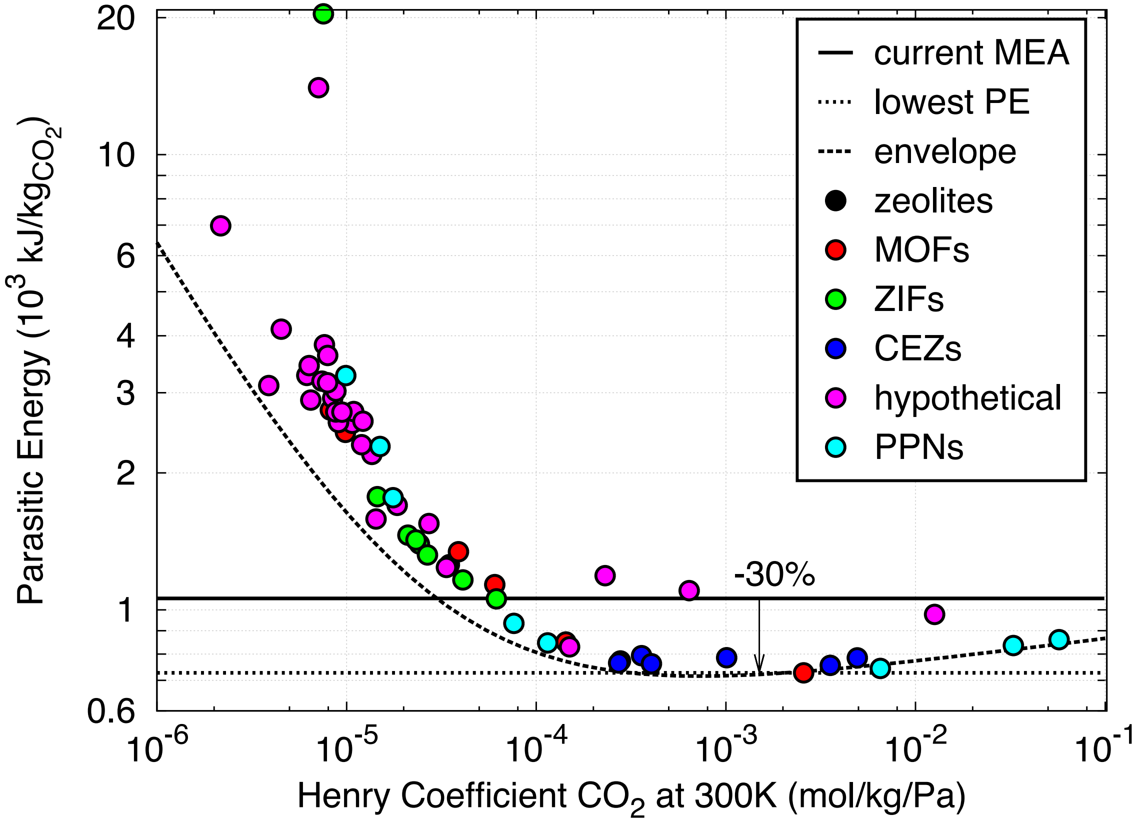
$\dot{Q}^+$

Research in new adsorbent

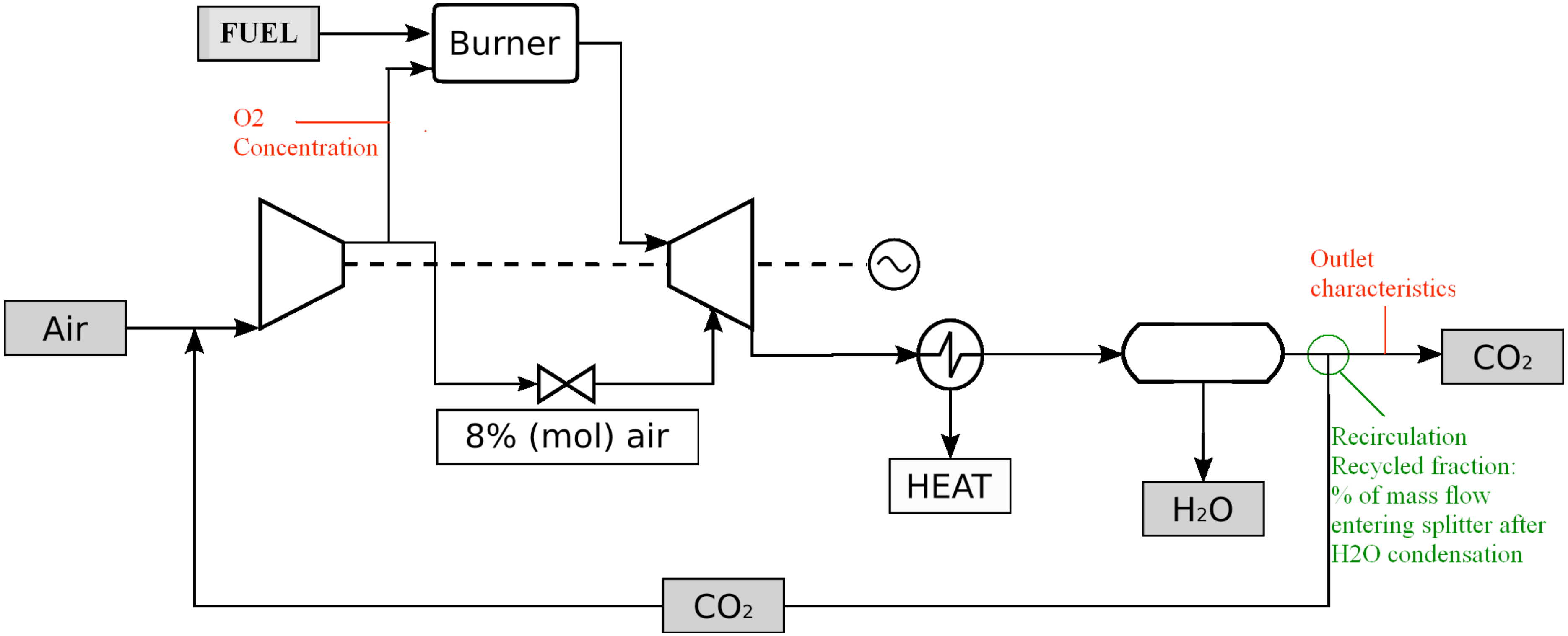
MOFs (Metal Organic Frameworks), Zeolites



Zn_4O(1,4-benzenedicarboxylate)$_3$
MOF-5



Increasing CO2 concentration

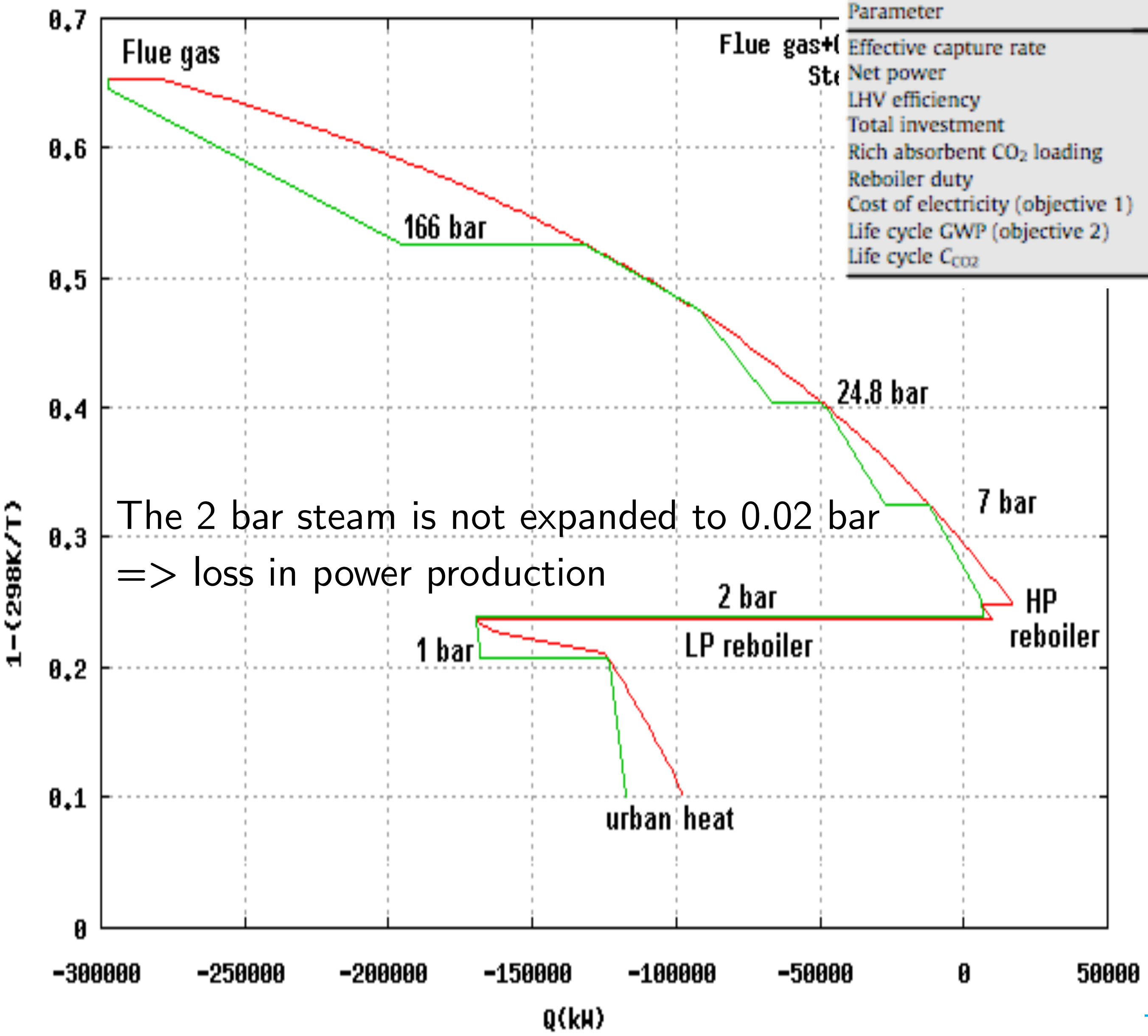


CO2 Recirculation allows for higher CO2 partial pressure in the absorber => lower investment cost
O2 excess lower in the burner => flame stability problems

Heat supply by cogeneration

Table 4
Additional details on the *b2* and *b5* designs.

Parameter	Unit	Design *b2*	Design *b5*
Effective capture rate	%	90.2	96.4
Net power	MW	363	360
LHV efficiency	%	54.5	54.0
Total investment	M$	351	357
Rich absorbent CO_2 loading	mol CO_2/mol MEA	0.465	0.461
Reboiler duty	GJ/ton CO_2 captured	3.45	3.46
Cost of electricity (objective 1)	$/MW h	78.31	79.85
Life cycle GWP (objective 2)	kg CO_{2eq}/MW h	111.9	88.4
Life cycle C_{CO2}	$/kg CO_{2eq}	62.43	62.67



The 2 bar steam is not expanded to 0.02 bar
=> loss in power production

Efficiency drops from 60% to 54% !

Investment :+ 30%
-> Cost of electricity +20 $/MWhe (+50%)

The heat of desorption reduces the electricity produced
Heat of adsorption can be recovered

Oxyfuel route

Fuel + O2 → CO2 + H2O

- No N2 in the flue gases
  - CO2 separation by condensing H2O
- O2 to be produced from Air
  - * needs a Air Separation Unit
  - * consumes Elec

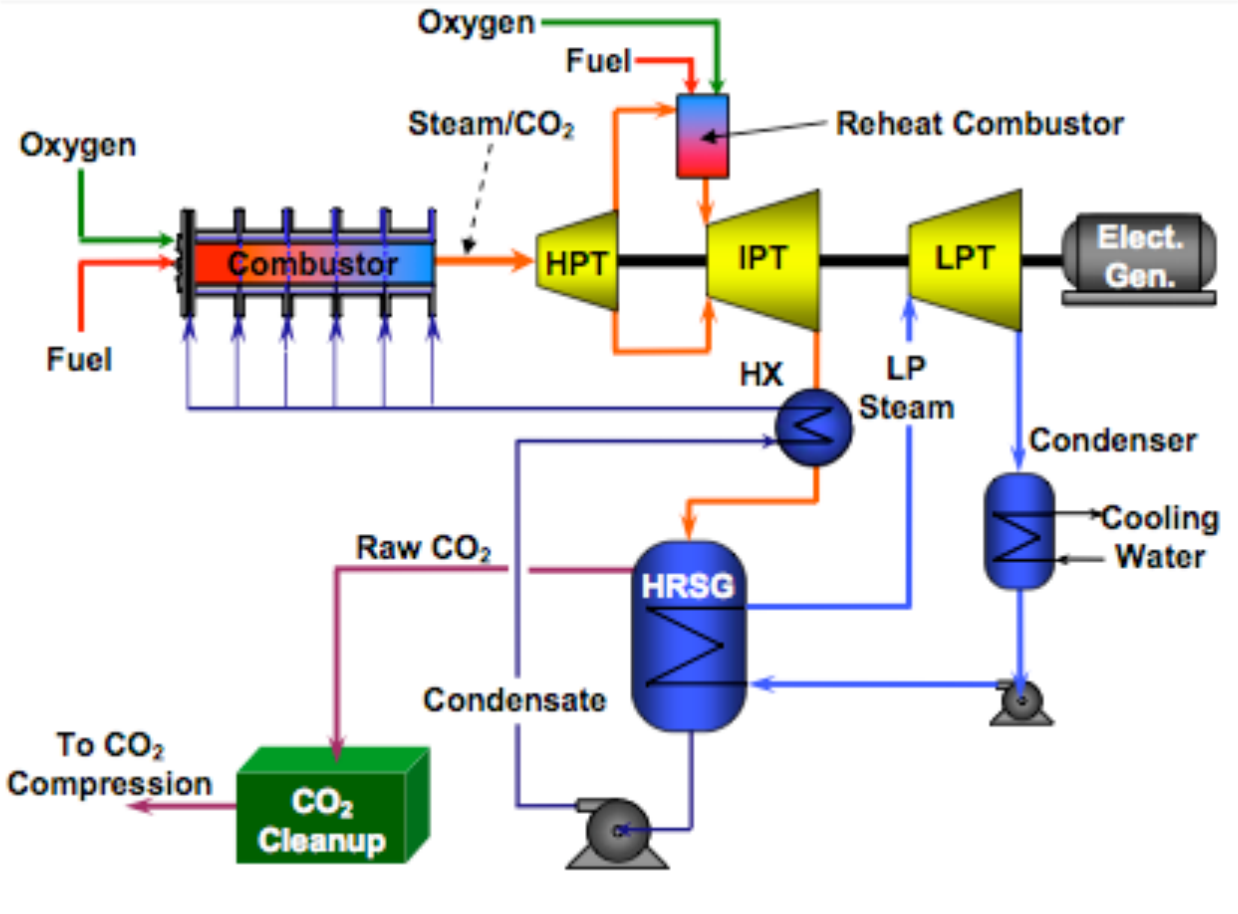


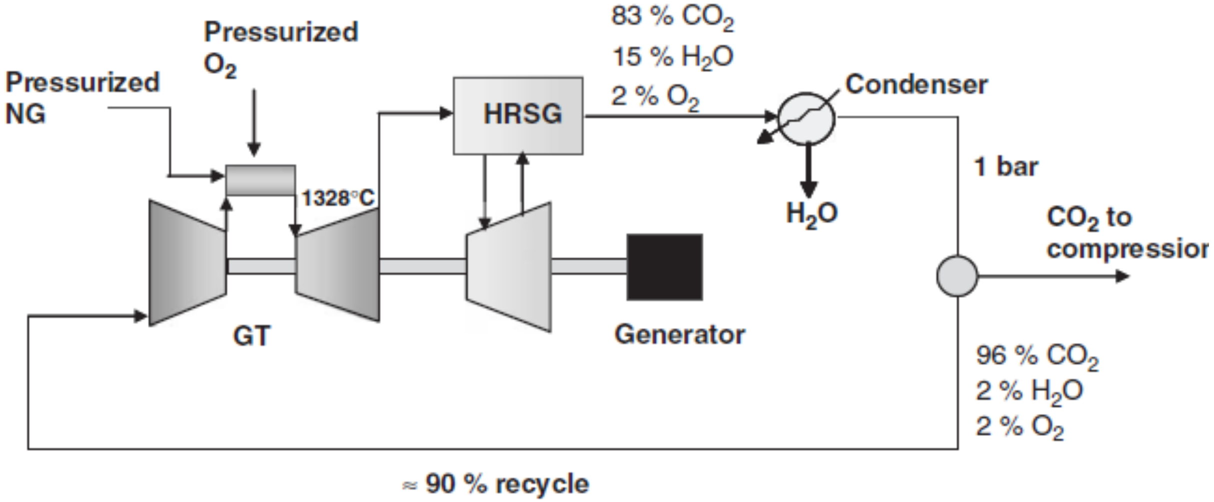
FIGURE 3. Conceptual Layout of CES Oxy-Fuel Cycle

Oxyfuel in gas turbine

- **Oxy-fuel combustion**
  - Matiant O_2/CO_2 cycle

Exhaust gas used as working fluid

CO_2 recycled to combustor to keep turbine inlet temperature (TIT) at required level

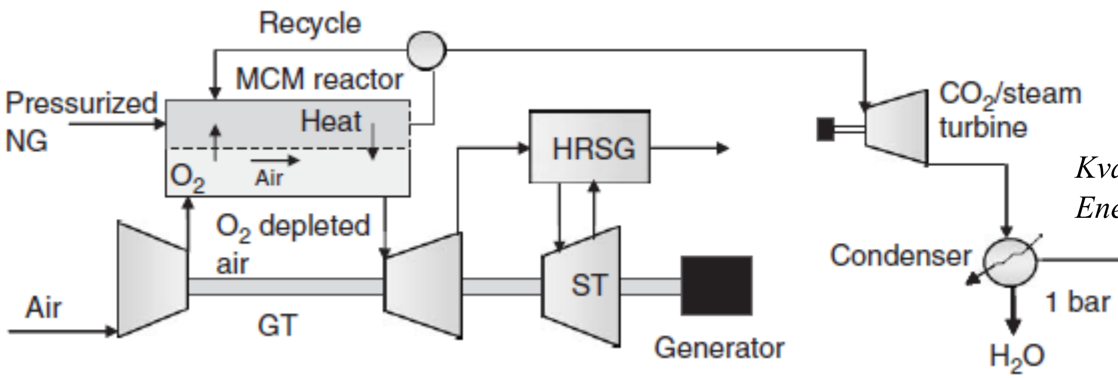


Kvamsdal et al. Energy 32 (2007)

- Matiant cycle: increase of efficiency by increasing the upper cycle pressure and inserting a reheat
- Efficiency: max 45%

Oxyfuel route : separation with membranes

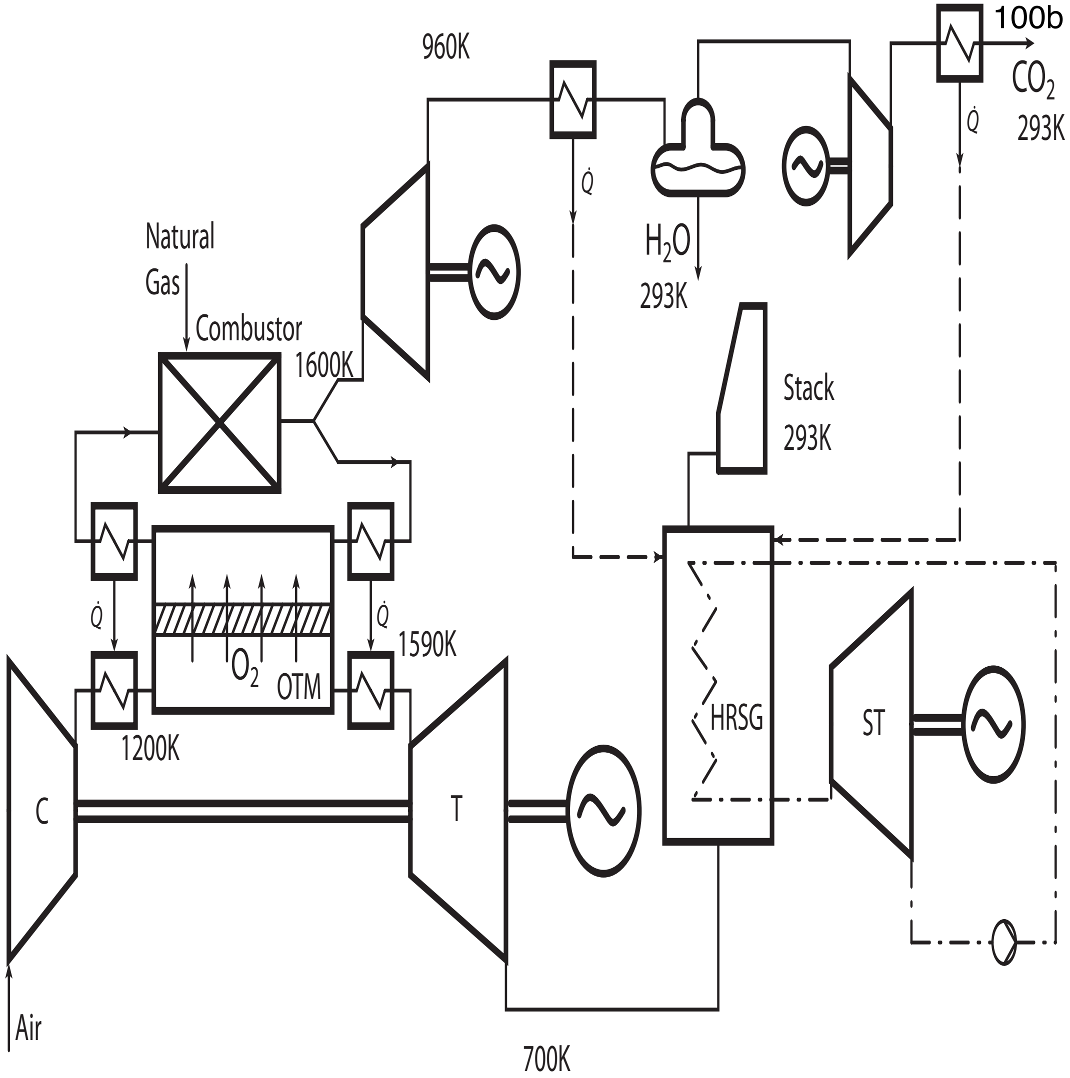
- **Oxy-fuel combustion**
  - AZEP (Advanced zero emission power plant) concept
  - Combustor replaced by mixed conductive membrane reactor (MCM)
    - Separation of O_2 from air by membrane
    - Near-to-stoichiometric fuel combustion
    - Heat exchange



Kvamsdal et al. Energy 32 (2007)

- Efficiency: 55-62%
- Specific cost: 690-1404$/kW

Oxy-fuel : AZEP Plant (Alstom)

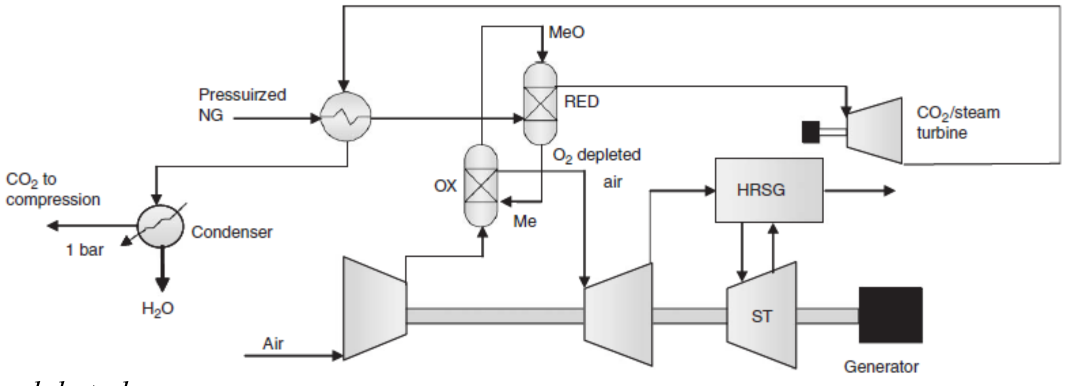


	Solution A	Solution B
Gas Turb. press. ratio	18	41
OTM inlet temp.	1200 K	1200 K
Oxygen sep. ratio	21.8%	31.2%
OTM outlet HX ΔT	100 K	97 K
Combustor out. temp.	1600 K	1600 K
Steam head. press.	101 bar	102 bar
	14 bar	13 bar
	2 bar	1 bar
Steam head. superh.	357 K	365 K
	311 K	214 K
	283 K	290 K
Condensate head. press.	0.021 bar	0.020 bar
ΔT multiplication factor	1	1
Specific Cost	690 US$/kW	1404 US$/kW
Efficiency	55.1%	62.5%

OTM : Oxygen separation membrane
Ceramic Separation membrane at high temperature (900 °C)

CO_2 capture concepts

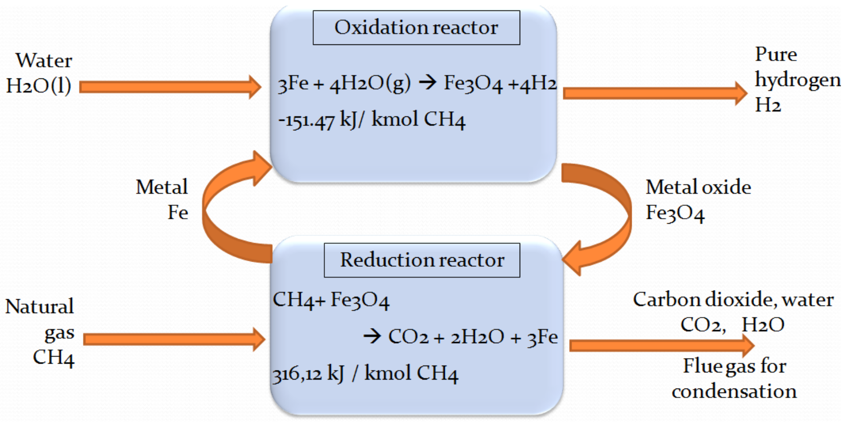
- **Oxy-fuel combustion**
  - **Chemical looping combustion (CLC)**
    - No direct contact between air and fuel
    - Combustion process split up into oxidation and reduction
    - Metal oxide as oxygen carrier



Kvamsdal et al. Energy 32 (2007)

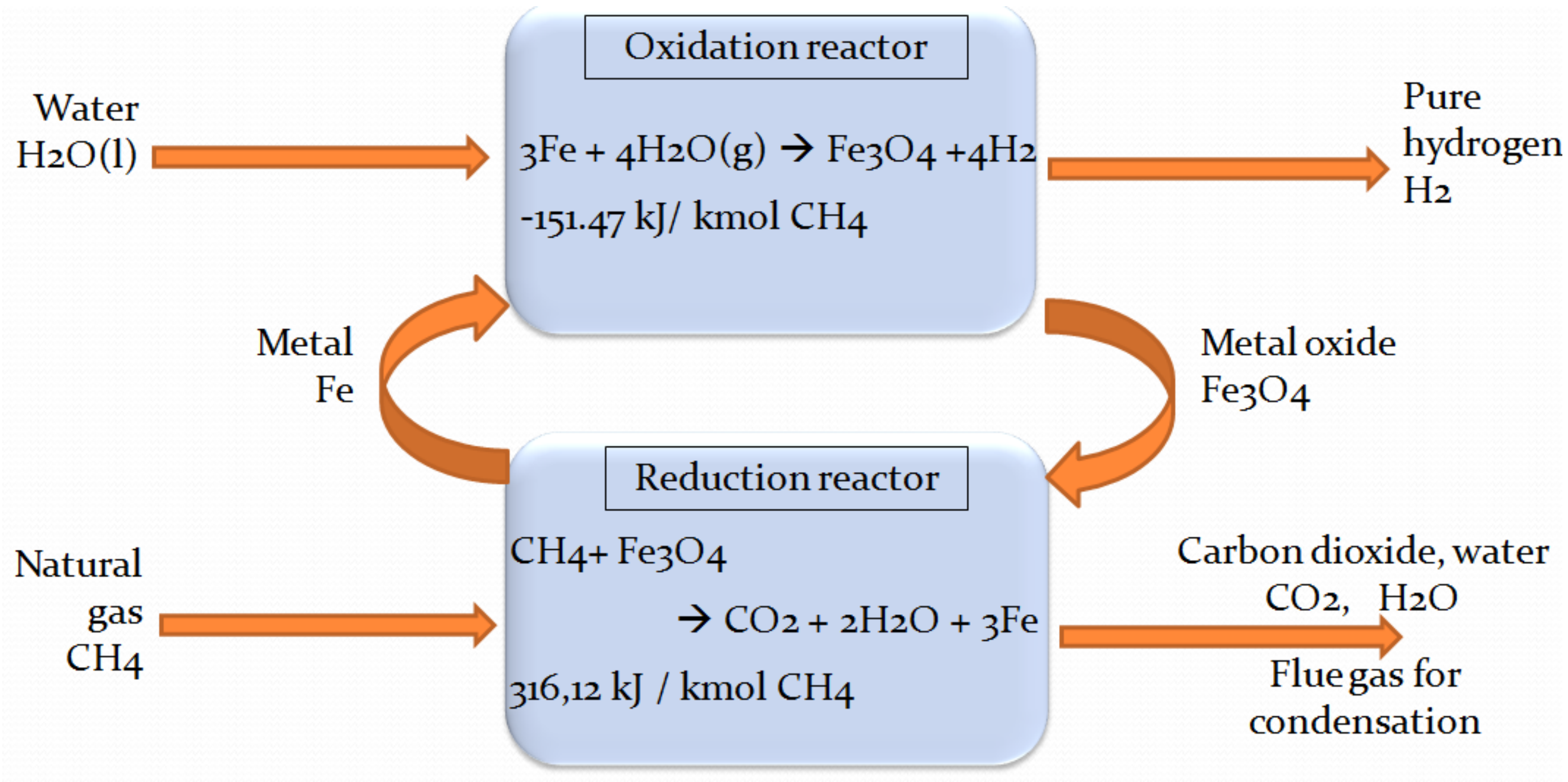
- Efficiency: 51%

- Alternative H_2 co-production



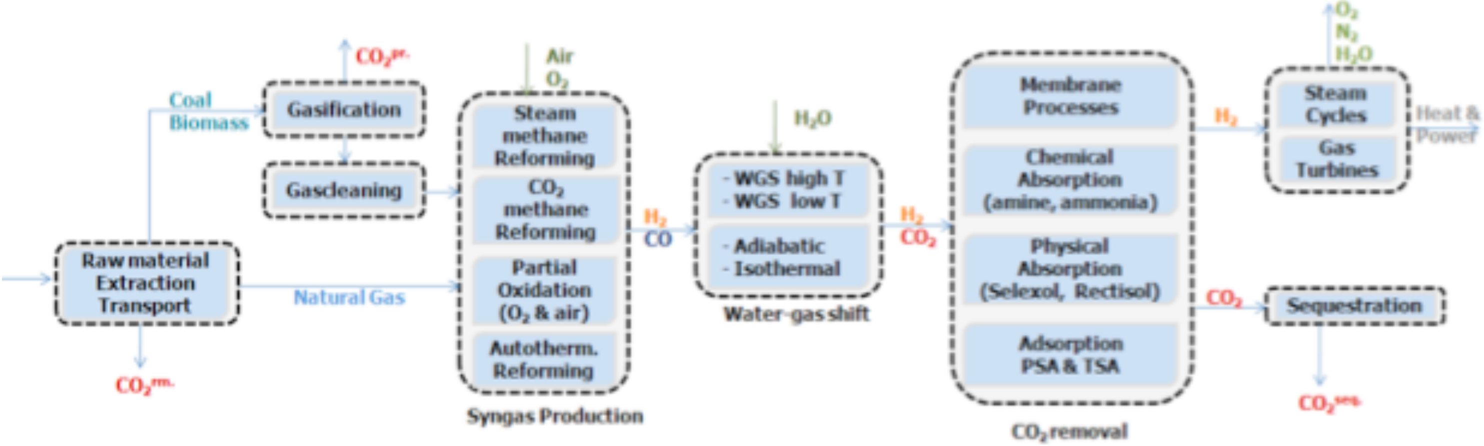
Courjon EPFL/LENI (2010)

Chemical looping



Courjon
EPFL/LENI (2010)

Hydrogen production routes



CxHy

↓

Steam Methane reforming

↓

CO + H2

↓

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2(\Delta h^0 = 206kJmol^{-1}) \quad (4)$$

$$C_nH_m + nH_2O \rightleftharpoons nCO + (\frac{m}{2} + n)H_2 \quad (5)$$

This reaction is equilibrated and takes place simultaneously with the shift reaction, therefore the resulting gas mixture always contains the four components.

Table 1. Reaction properties for a conventional steam methane reformer (SMR).

General info:	Endothermic reaction
Temperature	500 – 1000 ℃
Pressure	1 – 30 bar
Steam/methane ratio	2 – 3,5
Catalysts	Nickel- and aluminium oxide-based catalysts

Water gas shift reaction

↓

CO2 + H2

$$CO + H_2O \rightleftharpoons CO_2 + H_2(\Delta h^0 = -41kJmol^{-1}) \quad (6)$$

↓

H2/CO2 separation

↓

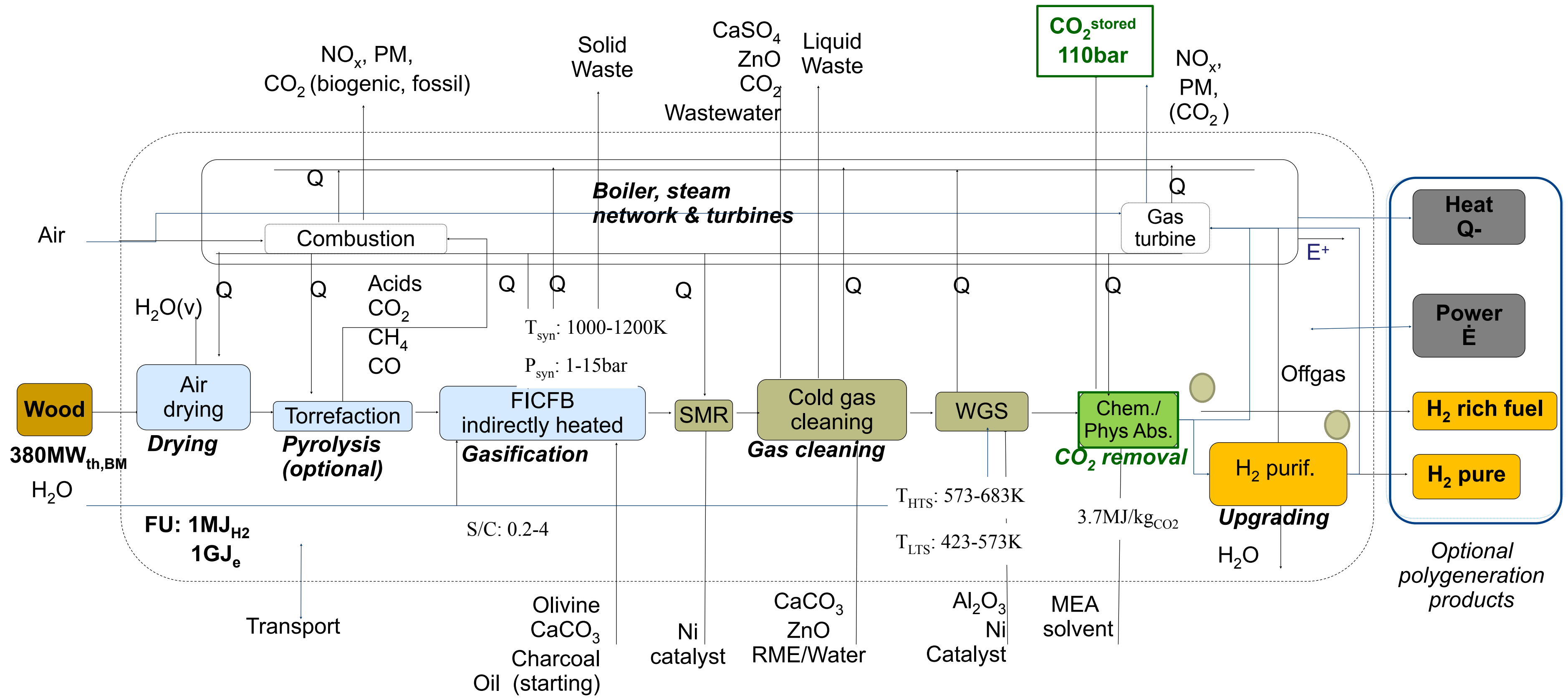
H2

CO2

CO2 is separated from the H2

H2 is then the fuel for a combined cycle or a fuel cell

Electricity production using biomass with CO2 capture



- Configurations (380$MW_{th,BM}$)
  - Without/with CO_2 capture (compression to 110bar)
  - H_2 process with Ė import or self-sufficient or Ė generation

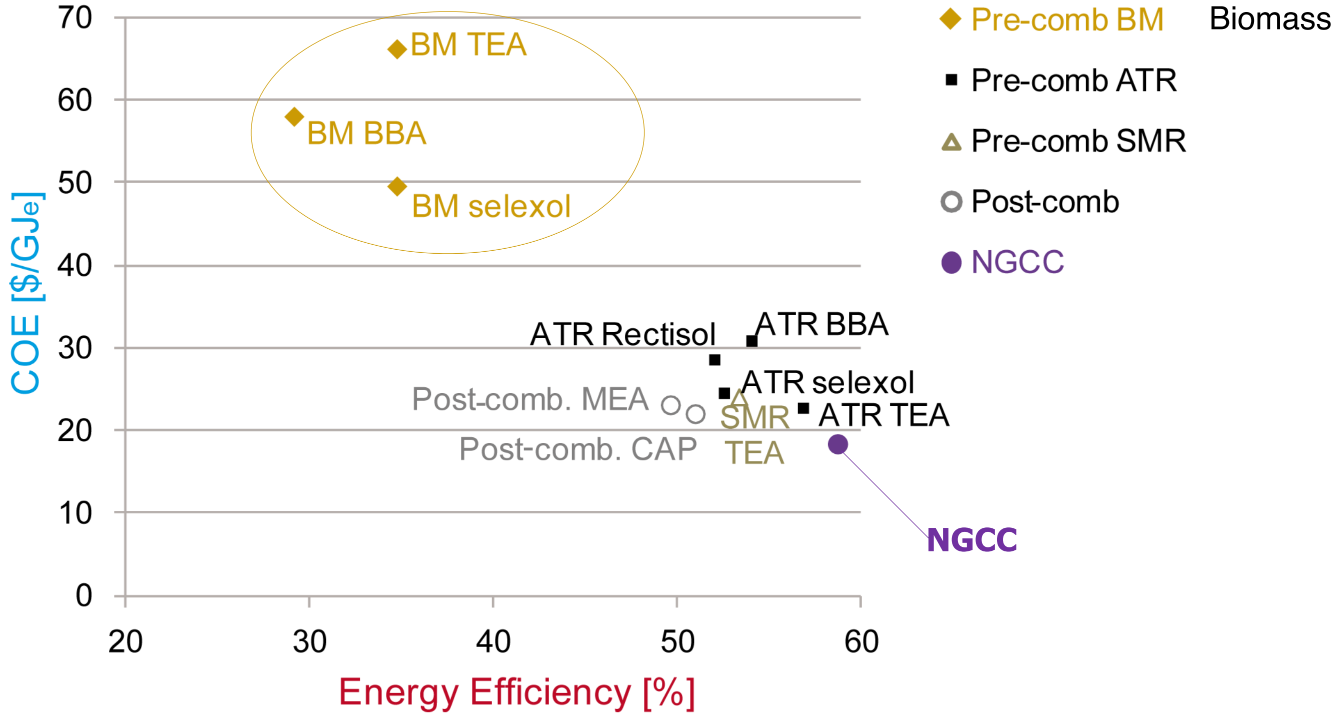
Negative emission plant

CO2 is biogenic (from atmosphere by photosynthesis)

BECCS : Biomass Electricity with carbon capture and sequestration

CO_2 capture energy and cost penalty

- Different process configurations
  - Natural gas fed processes 90% CO_2 capture, biomass 60% capture

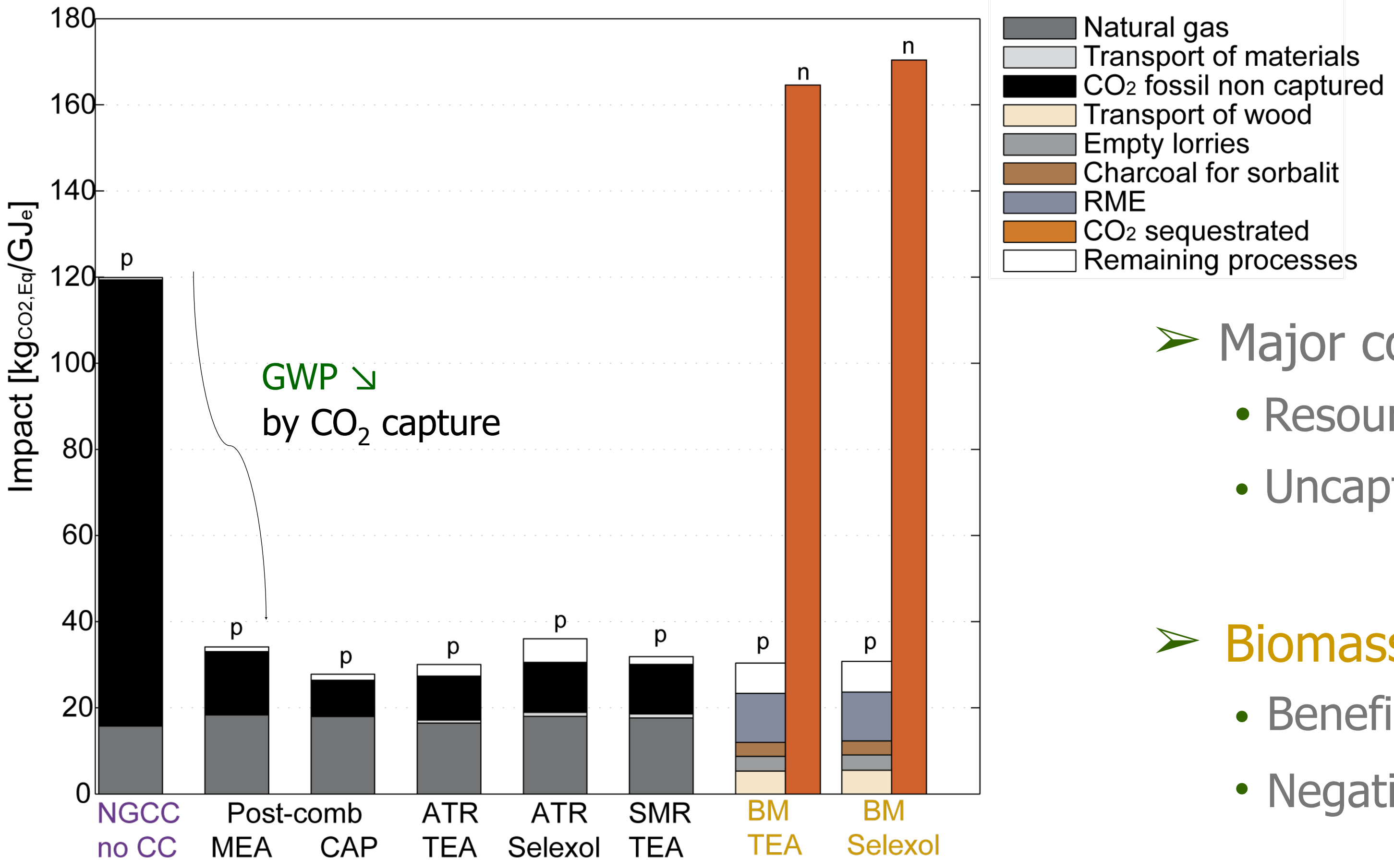


- Competition between post- and pre-combustion

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

CO_2 capture environmental performance

- IPCC 07: Global warming potential (FU=1GJe)



➢ Major contributions
- Resource extraction
- Uncaptured CO_2

➢ Biomass fed process
- Benefit of capturing biogenic CO_2 !
- Negative carbon balance !

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!

CO2 mitigation cost

Table 7
Performance of the different power plant options with CO_2 capture.

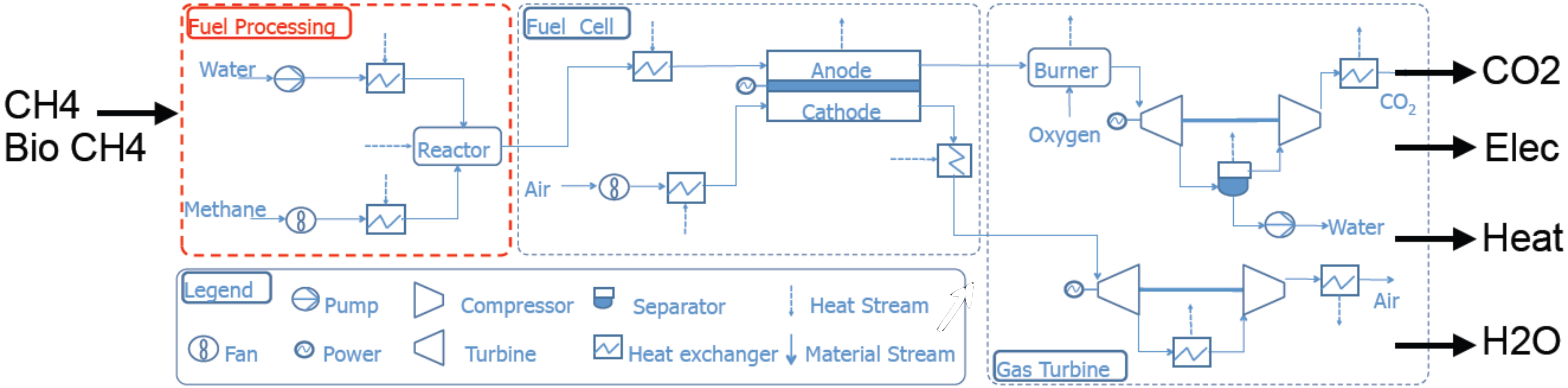
System capture technology	NGCC no CC	Post-comb MEA	Post-comb CAP	ATR TEA	ATR Selexol	SMR TEA	BM TEA	BM Selexol
Feed [$MW_{th,NG/BM}$]	559	587	588	725	725	725	380	380
CO_2 capture [%]	0	89.5	89.7	89.7	89.1	89.3	59	59
ϵ_{tot} [%]	58.75	49.6	50.9	56.8	52.6	53.3	34.8	34.8
	Power balance							
Net electricity [MW_e]	328	291	299	408	375	381	132	132
$\dot{E}^{+}_{consumption}$ [$MJ_e/GJ_{e,net}$]	–	108.3	44	91.9	146.6	48.1	342.4	342.4
$\dot{E}^{-}_{steamnetwork}$ [$MJ_e/GJ_{e,net}$]	340.7	341.3	301	200	177.6	143.8	346.2	346.2
$\dot{E}^{-}_{gasturbine}$ [$MJ_e/GJ_{e,net}$]	659.3	767	743	891.9	969	904.3	996.2	996.2
	Economic performance (assumptions Table 10 – base)							
Invest. [$/$kW_e$]	555	909	785	757	813	798.8	7380	3880
COE no CO_2 tax [$/$GJ_e$]	18.31	23.7	22.5	22.67	24.5	24.1	66.1	49.5
COE with CO_2 tax [$/$GJ_e$]	22	24.2	22.8	23.0	24.9	24.5	60.2	43.6
Avoidance costs [$/$t_{CO_2,avoided}$]	–	60	43	46	66	62	173	113
	Environmental performance (FU = $1GJ_e$)							
CO_2 emissions [kg_{CO_2}/GJ_e]	105	14.9	8.5	10.1	11.5	11.2	−170.4	−170.4
IPCC GWP [$kg_{CO_2,eq}/GJ_e$]	120	34	27.7	30	31.9	36.1	−139.6	−134.2
EI99 [pts/GJ_e]	7.48	7.7	7.7	7.7	8.1	9.0	6.2	6.1
Impact 2002 [10^{-3}pts/GJ_e]	28.9	20.8	20.3	21.5	22.4	25	2.9	3.2
CML acidification [10^{-2} $kg_{SO_2,eq}/GJ_e$]	20.1	14.9	15.4	20.6	21.8	24.3	21.3	21.1
CML eutrophication [10^{-3} $kg_{PO_4,eq}/GJ_e$]	39	23.6	24.4	37.7	40.6	43.5	95.1	95

Scenario	Base
Resource price [$/$GJ_{res}$]	9.7
Carbon tax[$/$t_{CO_2}$]	35
Yearly operation [h/year]	7500
Expected lifetime [years]	25
Interest rate [%]	6
Biomass feed [$MW_{(th)}$]	380
NG feed (post-comb) [$MW_{(th)}$]	725
NG feed (pre-comb) [$MW_{(th)}$]	590

Tock, Laurence, and François Maréchal. "Thermo-environomic optimisation strategy for fuel decarbonisation process design and analysis." *Computers & Chemical Engineering* 83 (2015): 110-120.

CO_2 capture

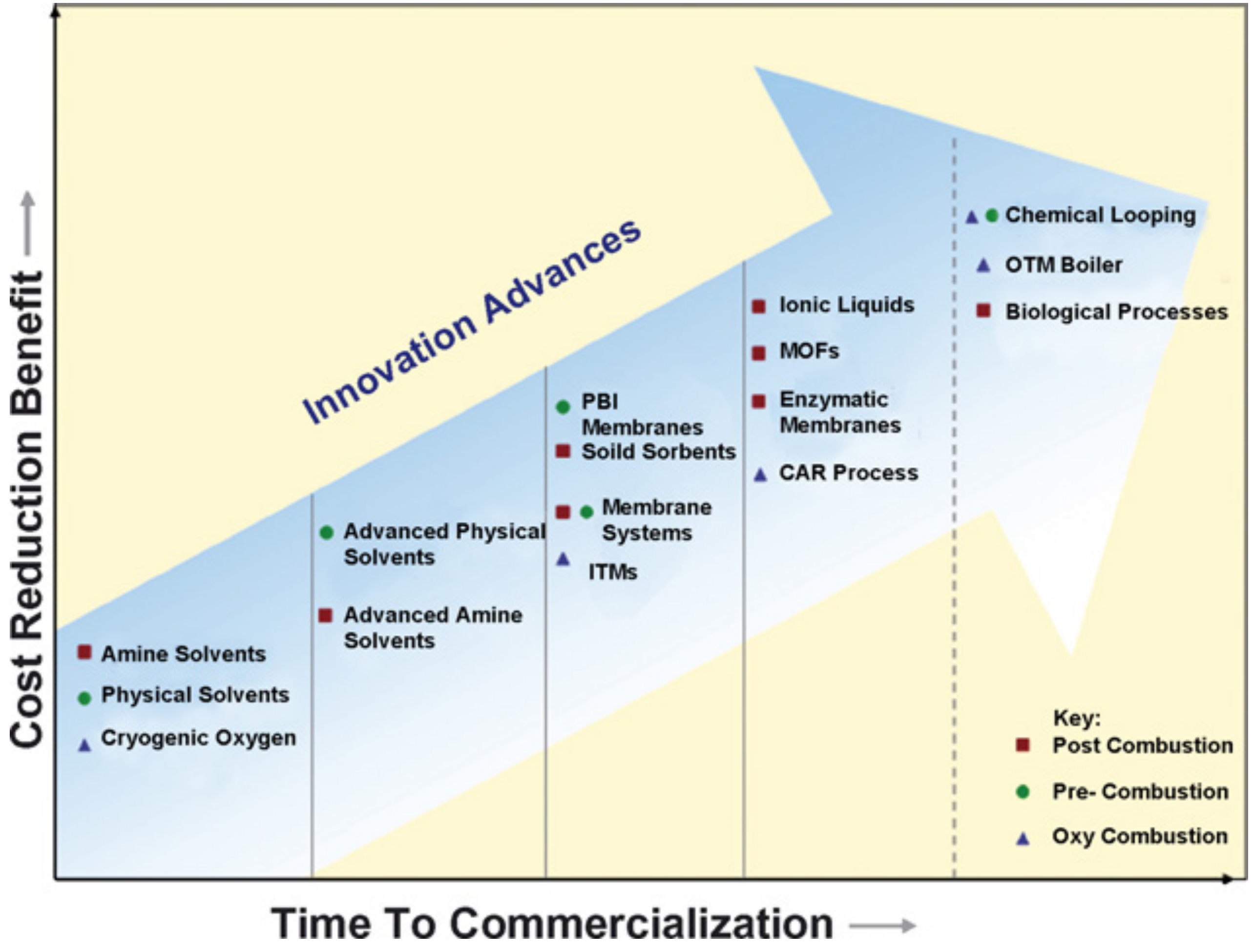
- **Fuel cell gas turbine hybrid system**
  - SOFC => O2 separation membrane
  - Innovative cycle with CO_2 capture
    - Energy efficiency 83%
    - Exergy efficiency >75%



E. Facchinetti
ECOS 2010

Facchinetti, Emanuele, Daniel Favrat, and François Marechal. "Innovative Hybrid Cycle Solid Oxide Fuel Cell-Inverted Gas Turbine with CO2 Separation." *Fuel Cells* 11.4 (2011): 565-572.

Carbon capture technology



[1] Figueroa, J. D.; Fout, T.; Plasynski, S.; McIlvried, H. & Srivastava, R. D. Advances in CO2 capture technologyâ€"The U.S. Department of Energy's Carbon Sequestration Program. *International Journal of Greenhouse Gas Control,* **2008**, *2*, 9 - 20