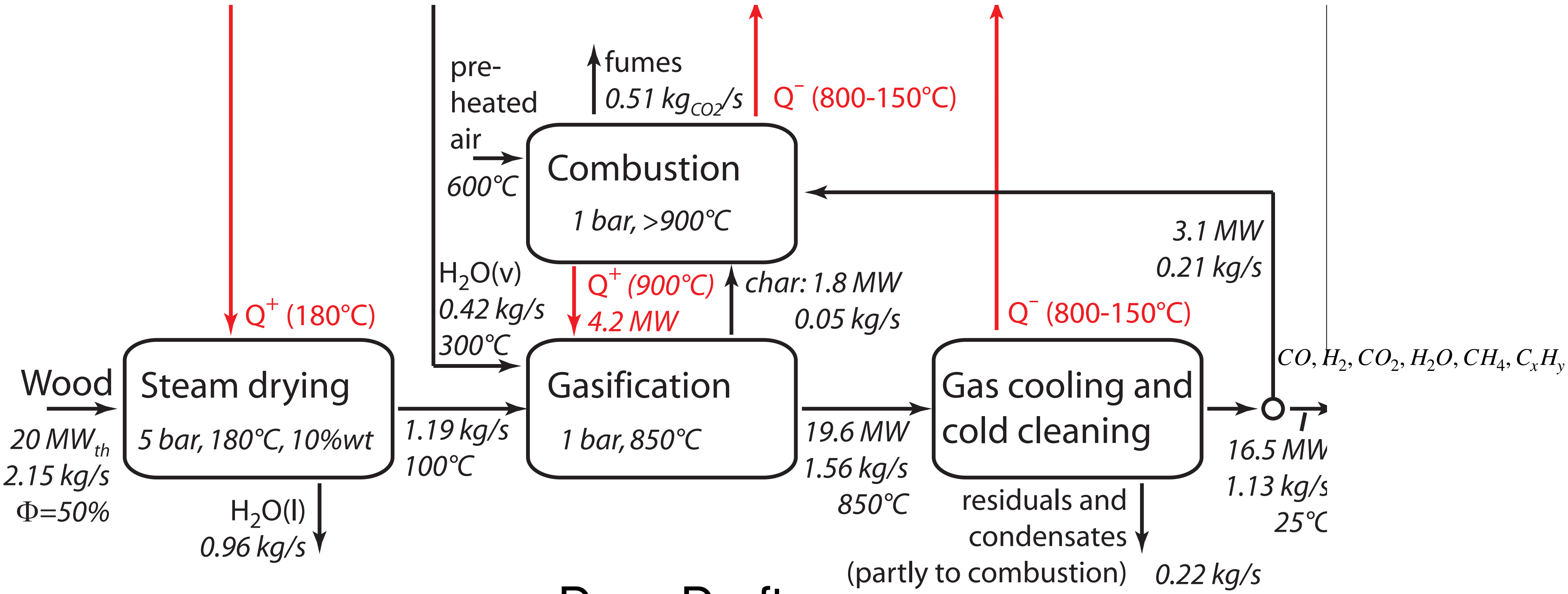
Thermochemical conversion of biomass

Electricity production from syngas

François Maréchal

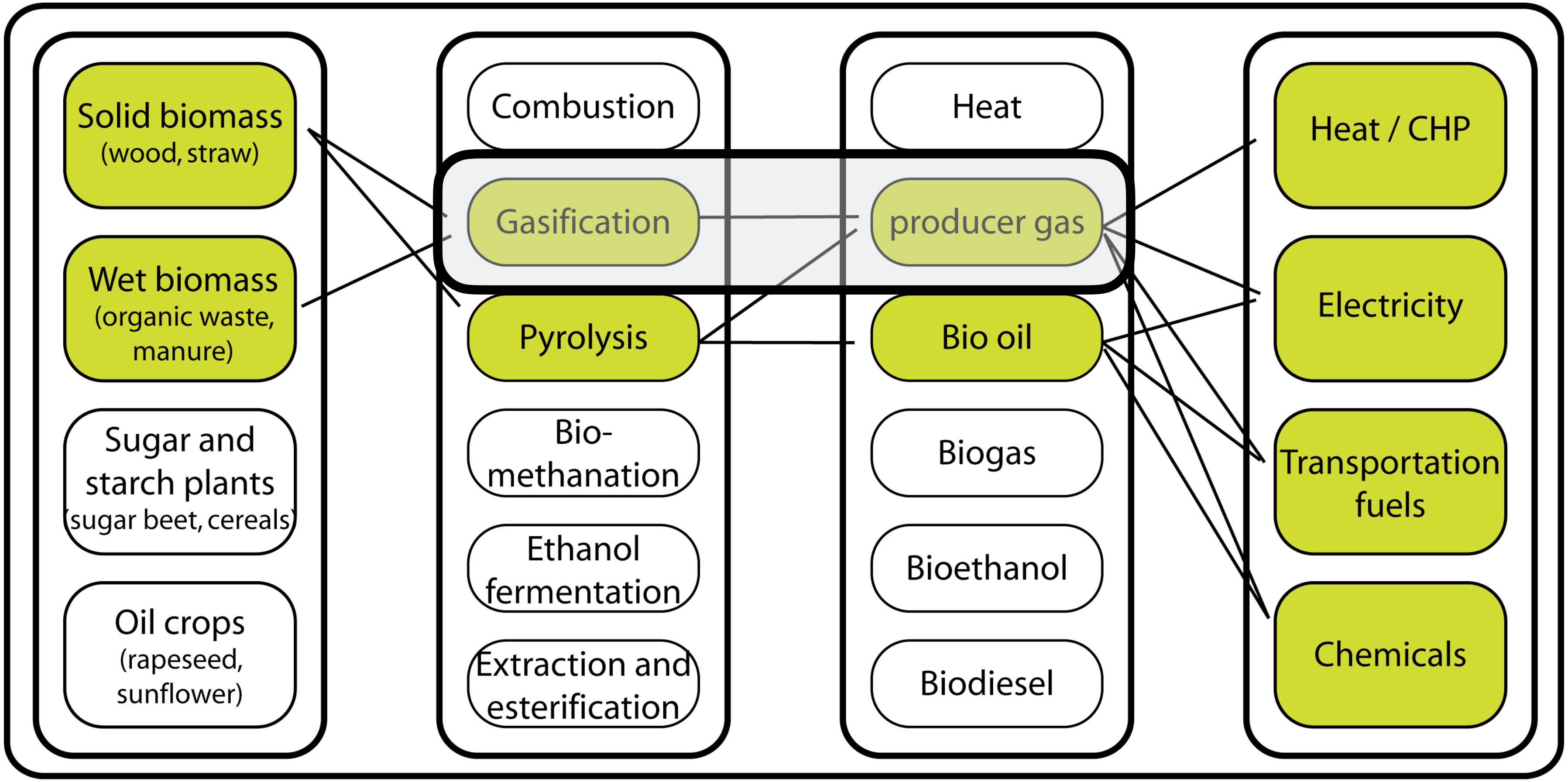
IPESE
Industrial Process and Energy Systems Engineering
EPFL Valais-Wallis
CH - 1950 Sion

SOLID -> SYNGAS



DownDraft
Entrained flow
Indirectly heated
Multi-stage

Biomass conversion
Thermochemical routes

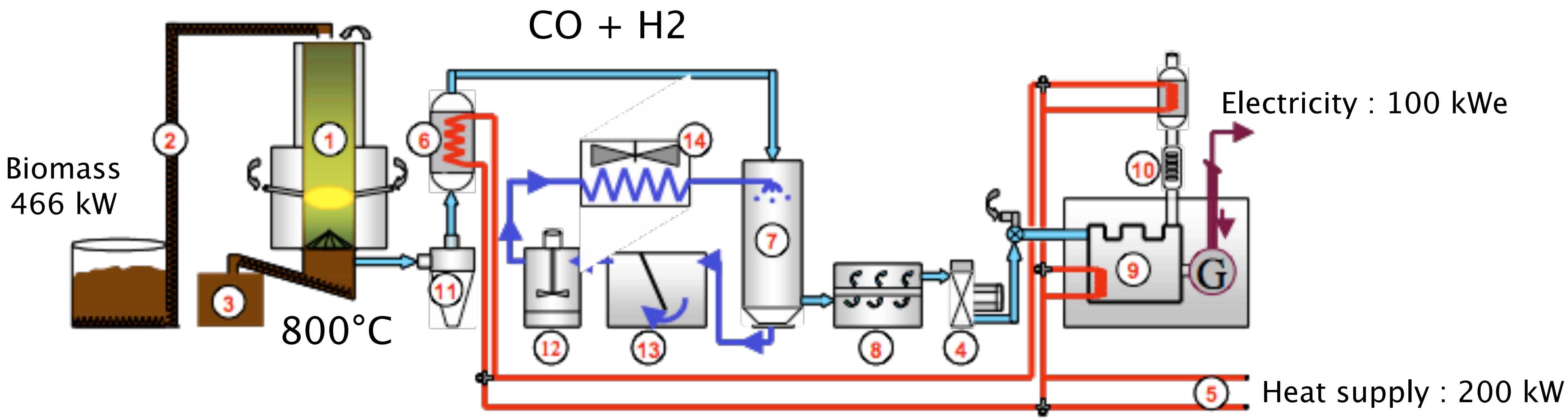


adapted from Chemical Engineering 10 (2006)

Cogeneration : Gasification

Gasification | Gas cleaning | Internal combustion engine

COMPOSANTS



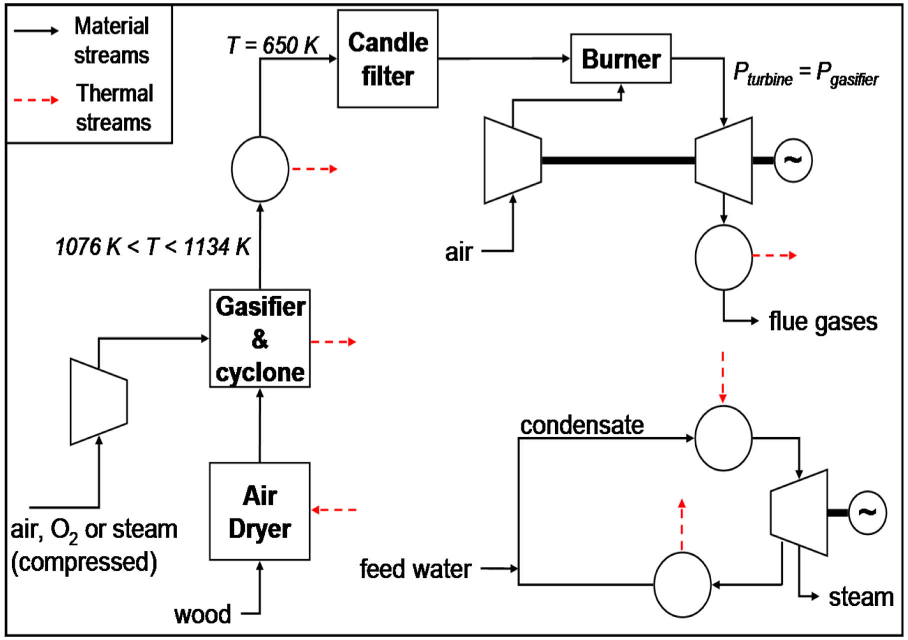
Légende :

1. Réacteur	6. Echangeur de chaleur	11. Cyclone
2. Chargement du bois	7. Colonnes de lavages	12. Cuve de floculation
3. Evacuation des cendres	8. Filtrations	13. Décanteur
4. Ventilateur	9. Moteur à gaz et génératrice	14 . Aéro-refroidisseur
5. Circuit de chauffage	10. Catalyseur	

MENAG MANAGEMENT SA
XYLOWATT SA

Energy flow diagrams of optimisation scenarios

Hot gas cleaning and gas turbine

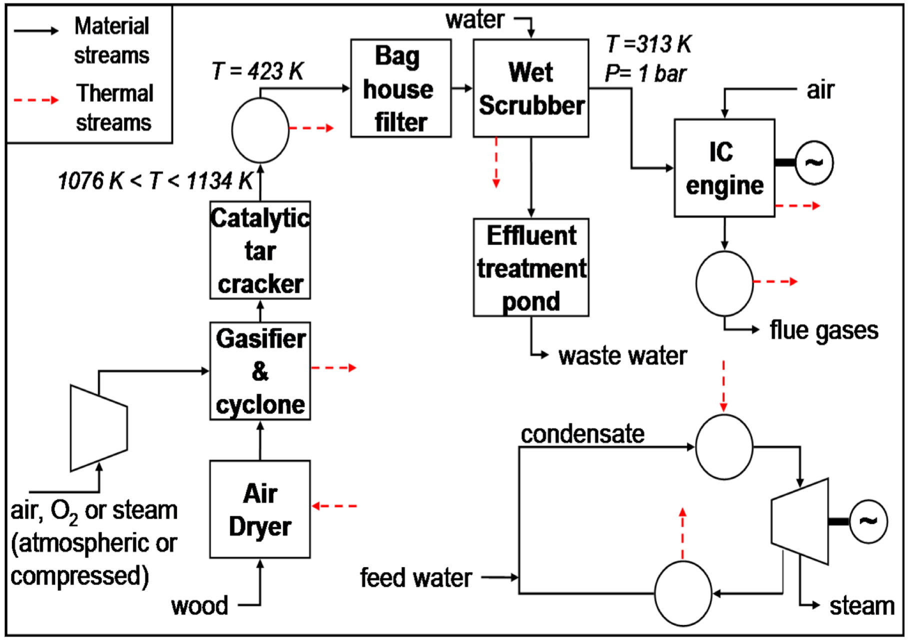


Hot Gas Cleaning (pros and cons)

+ no tar condensation (→ only particulates)

- Limited application
  - only gas turbine closed-coupled to gasifier
  - not feasible with IC engine
  - not possible to export syngas from site
- Cleaning technology not as established as CGC

Cold gas cleaning and IC engine



Cold Gas Cleaning (pros and cons)

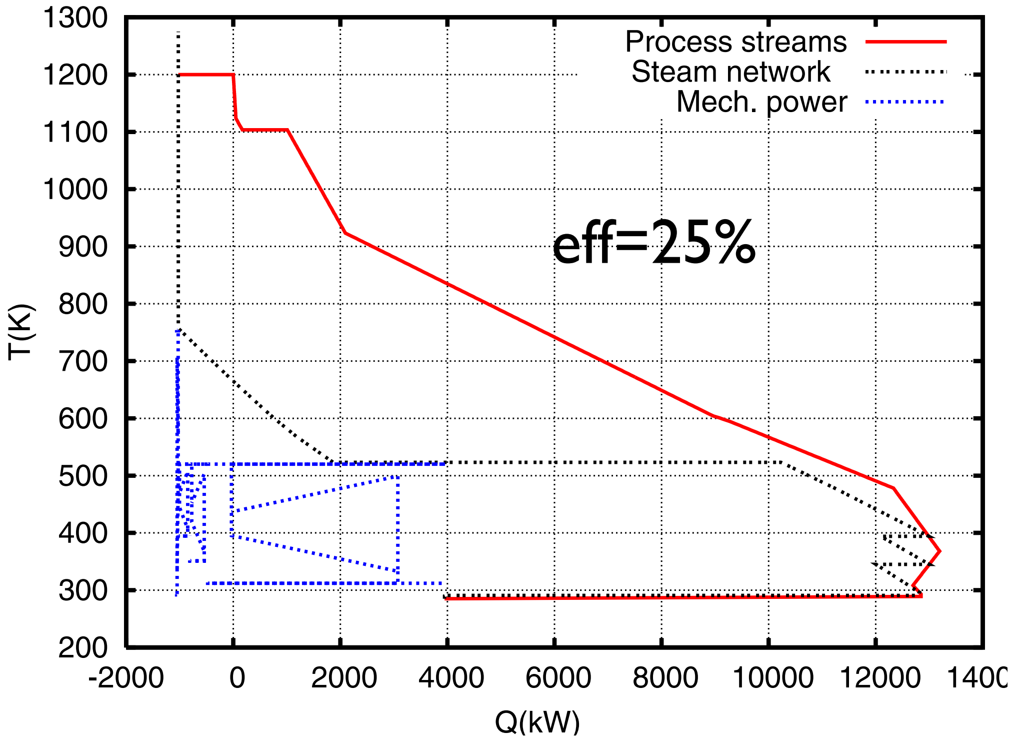
- tar condensation (→ tar disposal & equipment fouling concerns)

+ Flexibility
  + possible to export, or to further process syngas –e.g. SNG)
  + also feasible with gas turbine
+ Relatively mature cleaning technologies

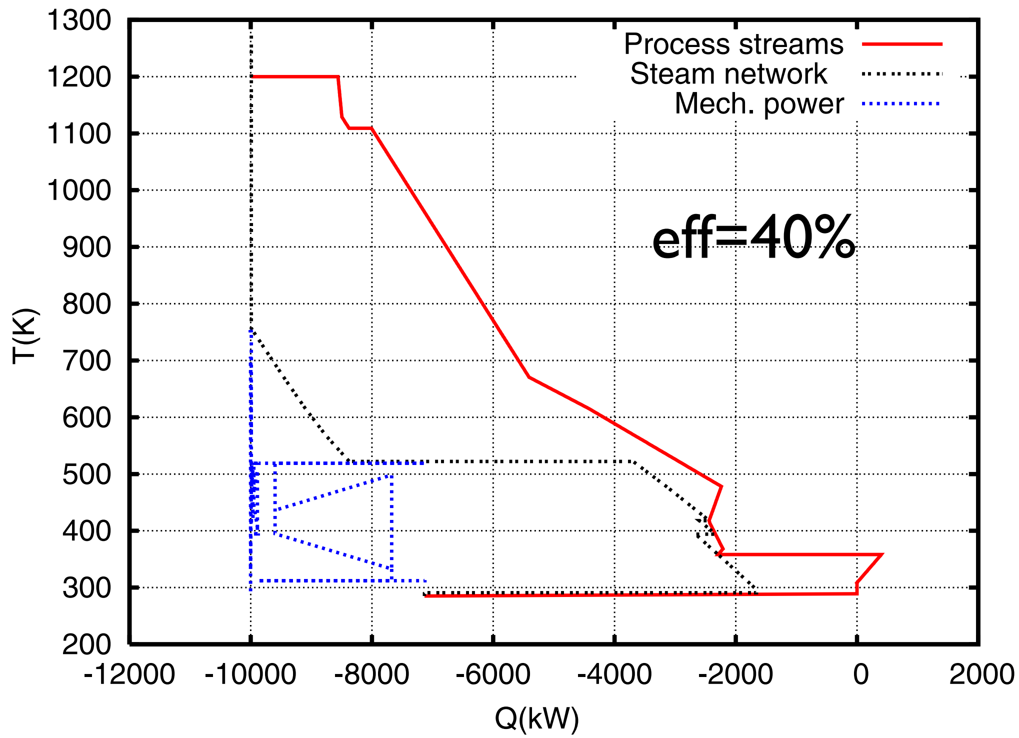
Reactor (n. iterations)		O_2 gasification (15000)		Air gasification (15000)		H_2O gasification (15000)	
	Units	Max eff.	Min cost	Max eff.	Min cost	Max eff.	Min cost
Invest. Costs	k€	29717	19129	32939	17122	26335	14339
Exergy eff.	-	0.32	0.13	0.33	0.10	0.34	0.19
Electric eff.	-	0.41	0.17	0.43	0.13	0.43	0.24
Cold gas eff.	-	0.63	0.28	0.65	0.27	0.78	0.81
Power	kWe	8269	3303	8534	2690	8685	4786
Specific cost	k€/kWe	3.59	5.79	3.86	6.37	3.03	3.00
Comp. curve	-	Not shown	Not shown	Fig. 5 left	Fig. 6 right	Not shown	Not shown
m.c wood	-	0.25	0.06	0.23	0.06	0.03	0.03
ER / SBR	-	0.25	0.25	0.25	0.25	0.34	0.33
P gasifier	bar	6.40	16.50	2.5	8.65	3.7	11.85
T gasifier	K	1123.5	1077.5	1134	1076	1119	1114
T inlet	K	753	737	611	591.5	753	749.5
Top. Cycle	-	ICE	GT	ICE	GT	ICE	GT

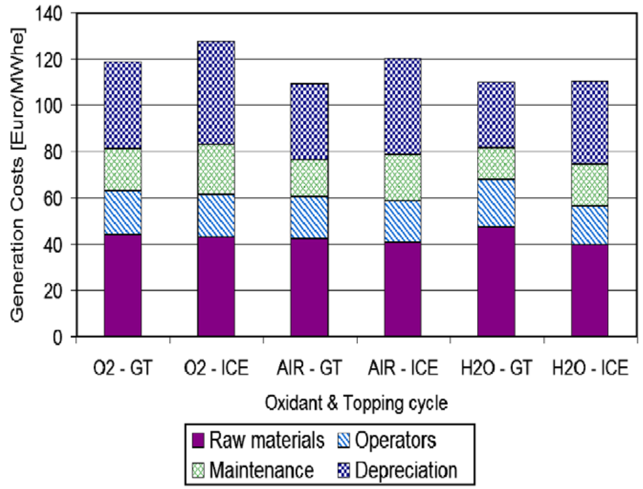
Integration with gas turbine

Gas turbine integration

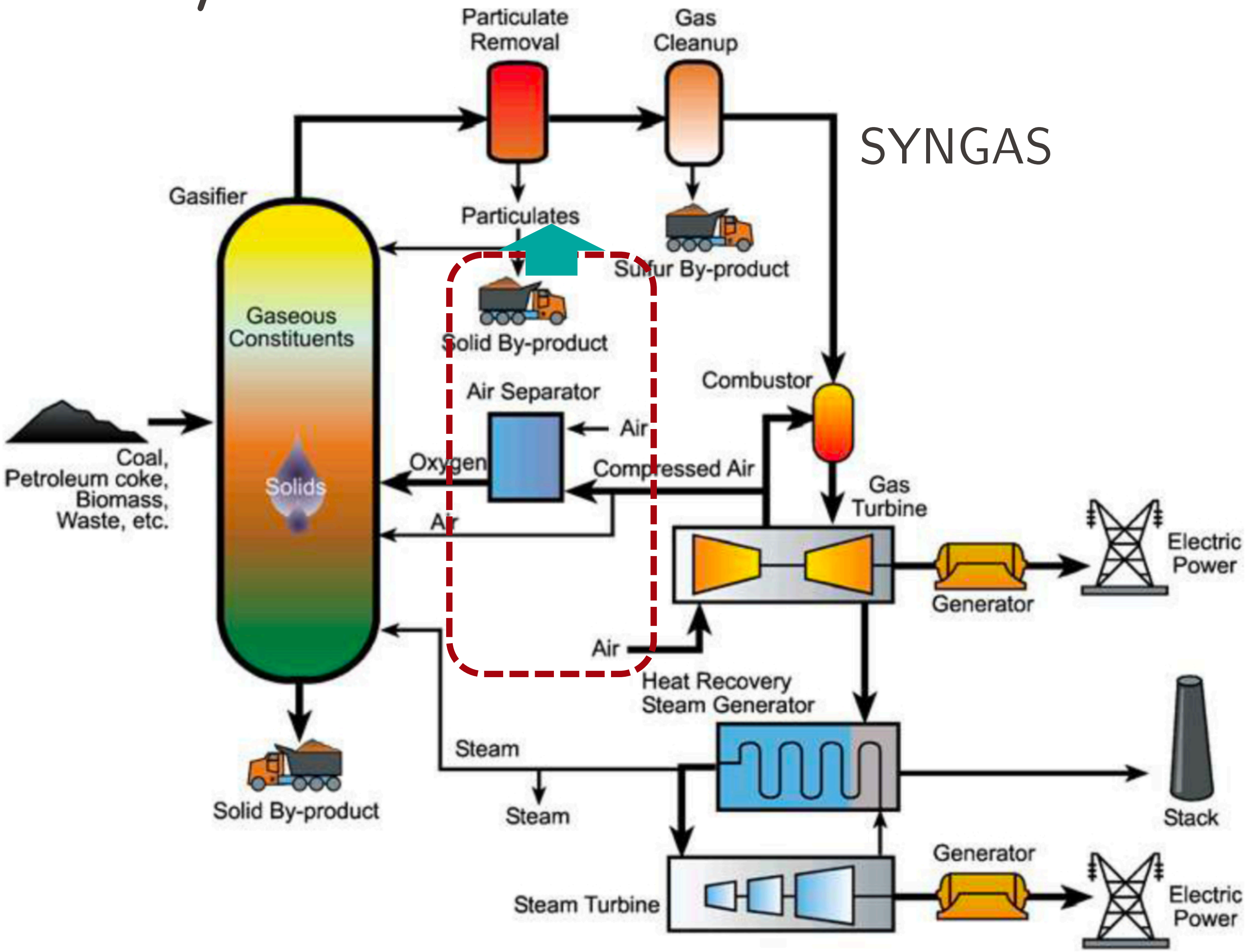


Gas engine integration





Biomass/Coal



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Integrating a fuel cell

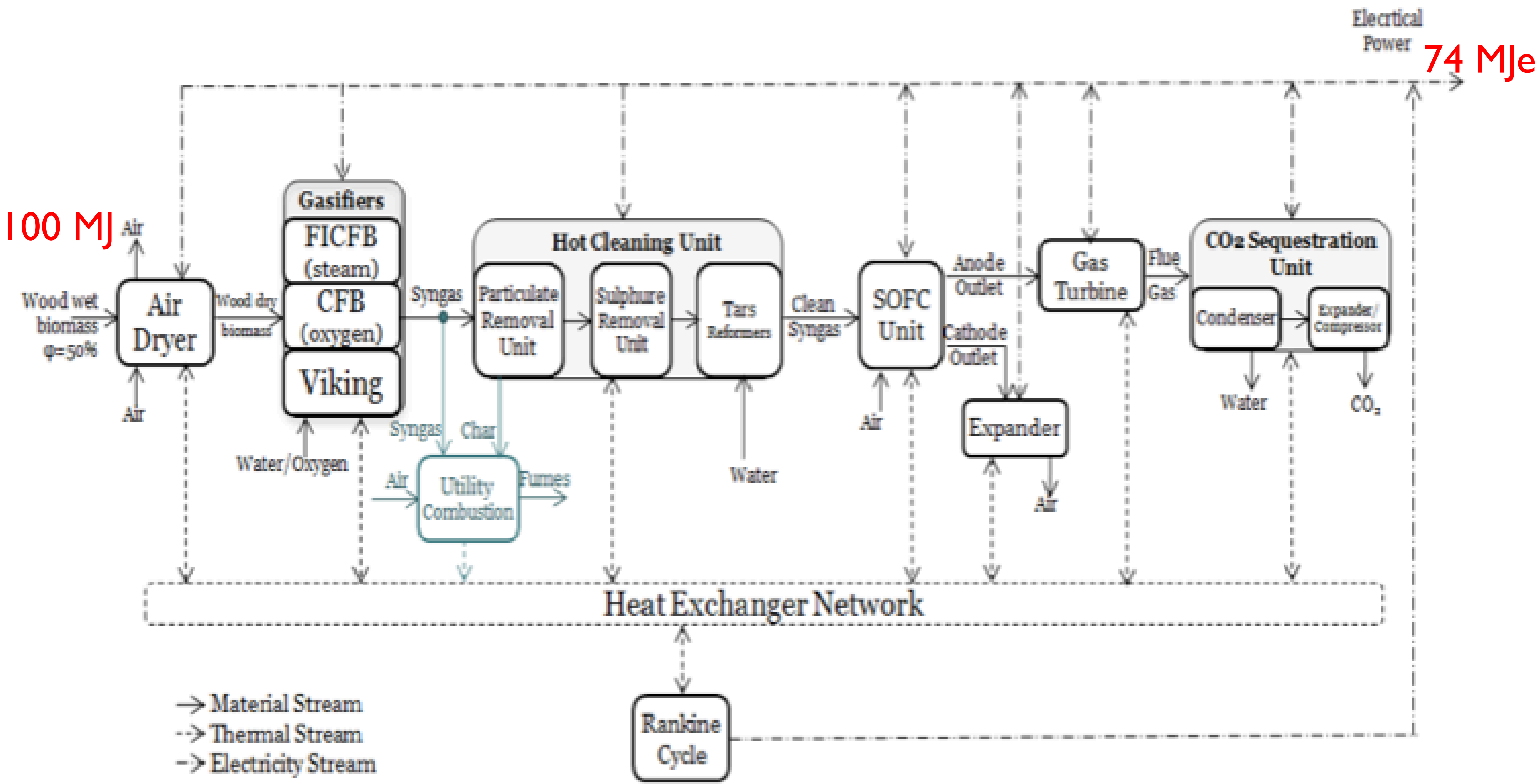
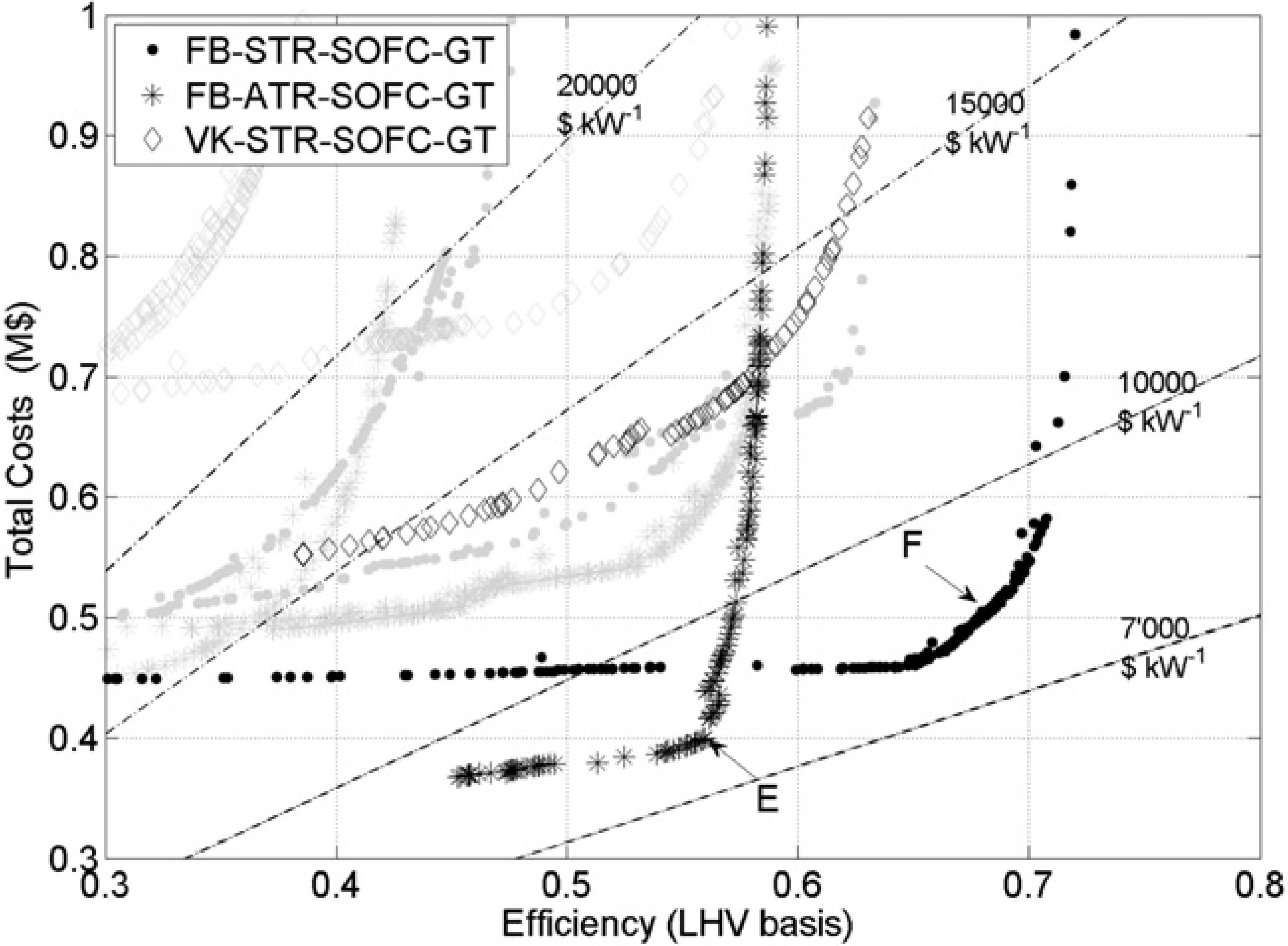


Table 1 – Summary of recent literature on biomass integrated gasification SOFC systems. Fixed: fixed bed gasifier; FB: Fluidized bed; GT: gas turbine (hybrid); ST: steam cycle (combined).

Reference	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]
Scale	100 kW	10.1 MW	250 kW	170 kW	200 kW	140 kW	1 MW	30 MW
Fuel composition mass fraction dry basis								
C (%)	49.3	55.5	[17]	51.2	n.a.	51.2	40	50
H (%)	5.9	5.55		6.1	n.a.	6.1	5.35	6.12
N (%)	0.6	–		0.76	n.a.	0.76	0.62	0.55
O (%)	44	38.9		39.3	n.a.	39.3	44.5	42.5
S (%)	0.02	–		0.09	n.a.	0.09	0.15	0.06
Cl (%)	0.162	–		–	n.a.	–	–	–
Ash (%)	–	–		2.6	n.a.	2.6	9.41	0.8
Moisture (%ar)	12	10		10	n.a.	10	10	25.2
Equip. specs								
Type gasifier	Fixed	n.a.	Viking	FB	FB	FB	FB	Circ. FB [18]
Oxidizing agent	Air	Cathode air	Air	Steam	Air	Steam	Steam	Air
Gasifier temp (K)	1073	1573	–	1073	1173	1073	1223	1223
Min. gas cleaning temp. (K)	873	817	573	723	573	343	973	n.a.
TAR reformer	Yes	Yes	No	Yes	No	Yes	No	Yes
Type SOFC	Ni/GDC LSM	n.a.	Risø [19]	n.a.	Planar int. ref.	Ni/YSZ LSM/YSZ	n.a.	n.a.
SOFC outlet temp. (K)	1273	1268	1073	1173	1223	1173	1073	1223
Current density (A cm^{-2})	0.25	n.a.	0.3	0.3	n.a.	0.25	0.37	0.25
Fuel utilization (%)	85	80	85	85	n.a.	70	85	80
SOFC recirculation	Anode, cathode	n.a.	Anode, cathode	–	–	–	–	Anode, cathode
Auxiliary	Micro-GT	GT	GT (η 75%)	–	–	–	ST (η 75%)	GT (η 91%)
Turbine inlet temp. (K)	1273	1473	1173	–	–	–	–	1393
Maximum pressure (MPa)	0.7	n.a.	0.25	0.1013	0.1013	0.3	0.5	0.8
Heat exchangers	7	2	6	3	2	3	6	5
Max. eff. LHV (%)	54	42	50	34	23	36	64.4	50

Morandin, Matteo, François Maréchal, and Stefano Giacomini. "Synthesis and Thermo-economic Design Optimization of wood-gasifier-SOFC Systems for Small Scale Applications." *Biomass and Bioenergy* 49 (2013): 299–314.

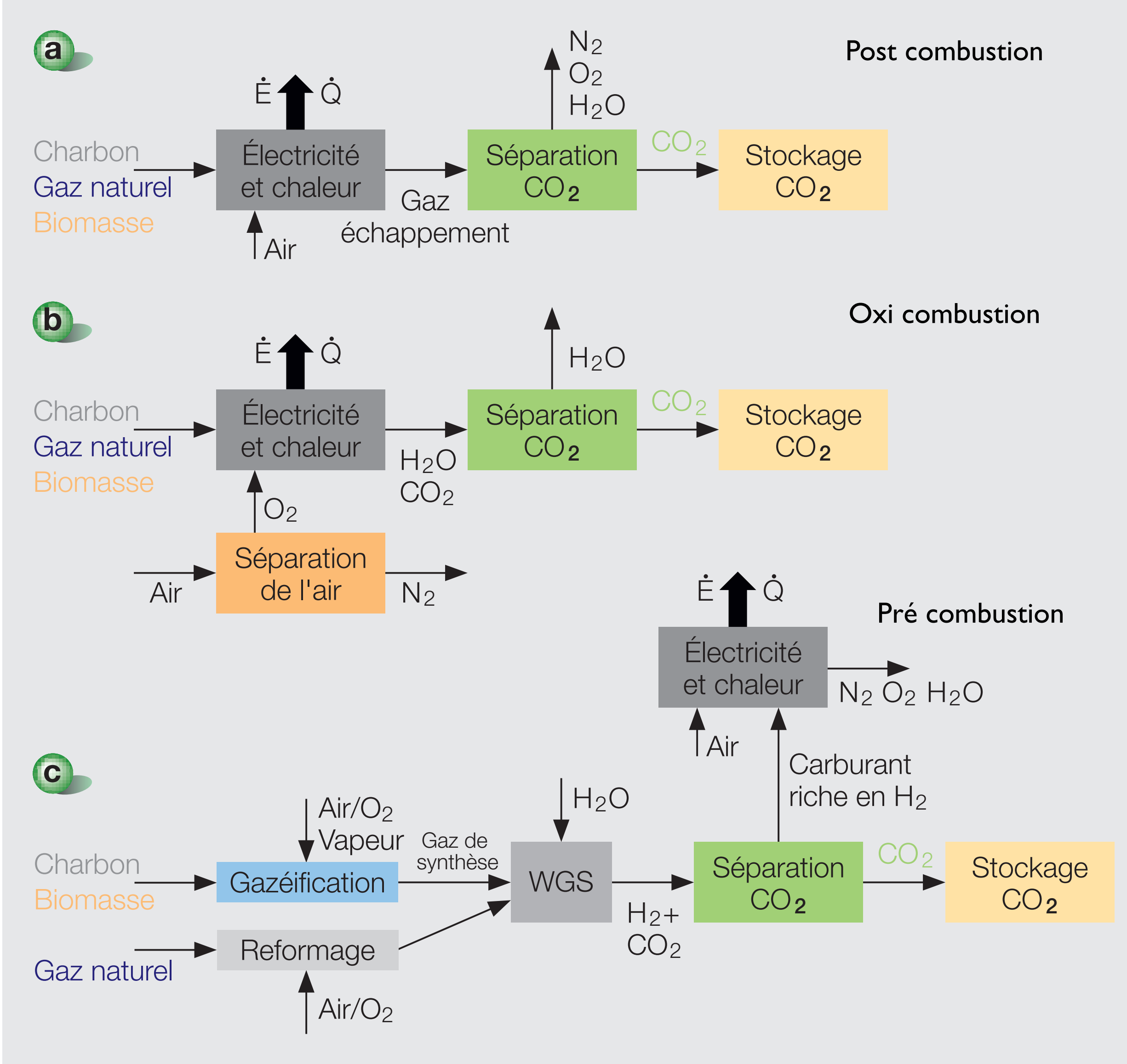

FB-STR-SOFC-GT
FB-ATR-SOFC-GT
VK-STR-SOFC-GT
20000 $ kW-1
15000 $ kW-1
10000 $ kW-1
7'000 $ kW-1
F
E
Total Costs (M$)
Efficiency (LHV basis)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.3
0.4
0.5
0.6
0.7
0.8

SOFC-Gasifiers

		Small size		Medium size		
Parameters	Unit	FICFB_NP_S	VKG_S	FICFB_NP_M	FICFB_P_M	CFB_M
Humidity wood dryer outlet	%	0.16	0.21	0.11	0.11	0.11
Steam/biomass ratio	-	0.76	-	0.85	0.9	0.56
Steam to carbon ratio in the reformers	-	1	1.08	1.12	1.86	1
Fuel cell Inlet temperature	K	1026	1023	101	1011	1022
Steam excess ratio in the post combustor	-	0.30	0.26	0.27	0.23	0.32
Energy efficiency	[%]	**64.5**	**68.7**	**65.6**	**67**	**71%**
Specific investment cost	[$/kW]	22048	27196	11113	10280	9305
Specific Cost (electricity output)	[$/kWh el]	**1.03**	**1.10**	**0.35**	**0.33**	**0.30**
Specific Cost (biomass input)	[$/kWh th,BM]	0.63	0.71	0.21	0.20	0.19

CO2 Capture

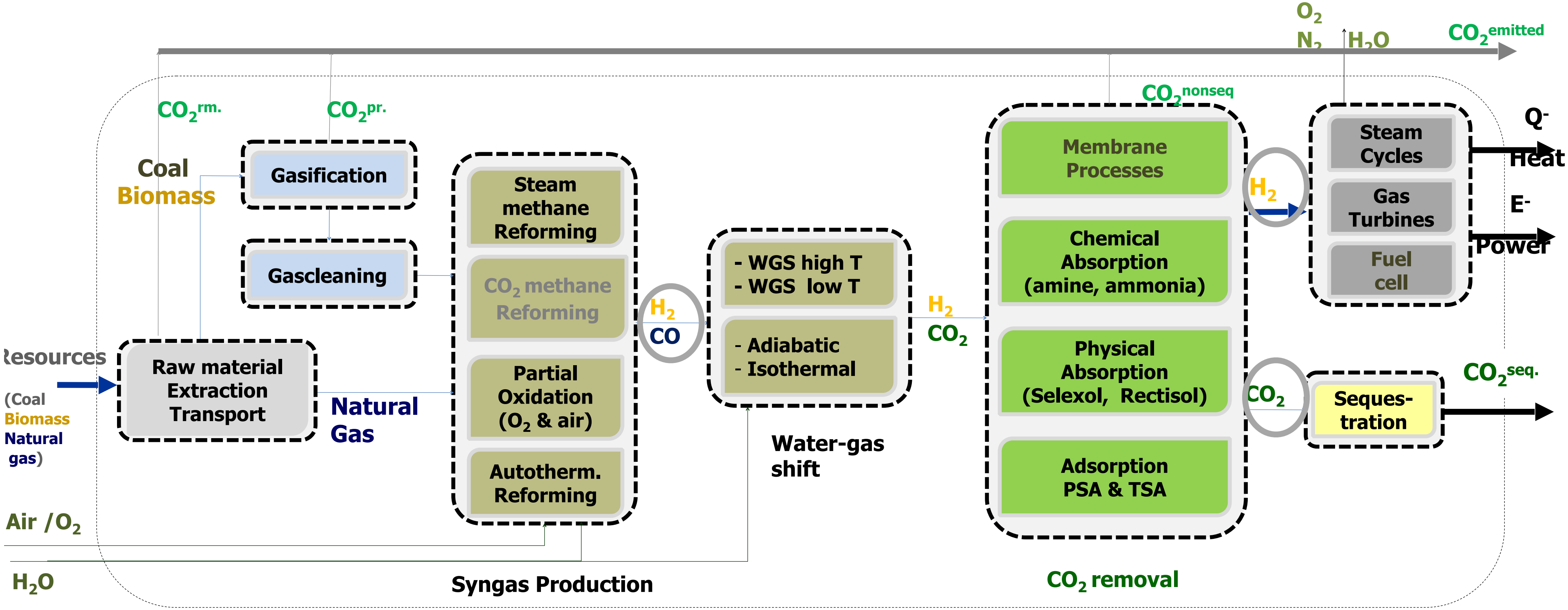
- NG Penalty
  - Compression
    - 2% (LHV)
  - Capture :
    - 4-7% (LHV)
  - Total
    - 6 à 9% (LHV)
- Investissement
  - + 30%



L. Tock and F. Marechal, La capture de CO2 dans les centrales électrique, réduction des émissions de CO2 par CCS, Bulletin SEV/ASE, Nov. 2013

Physical model

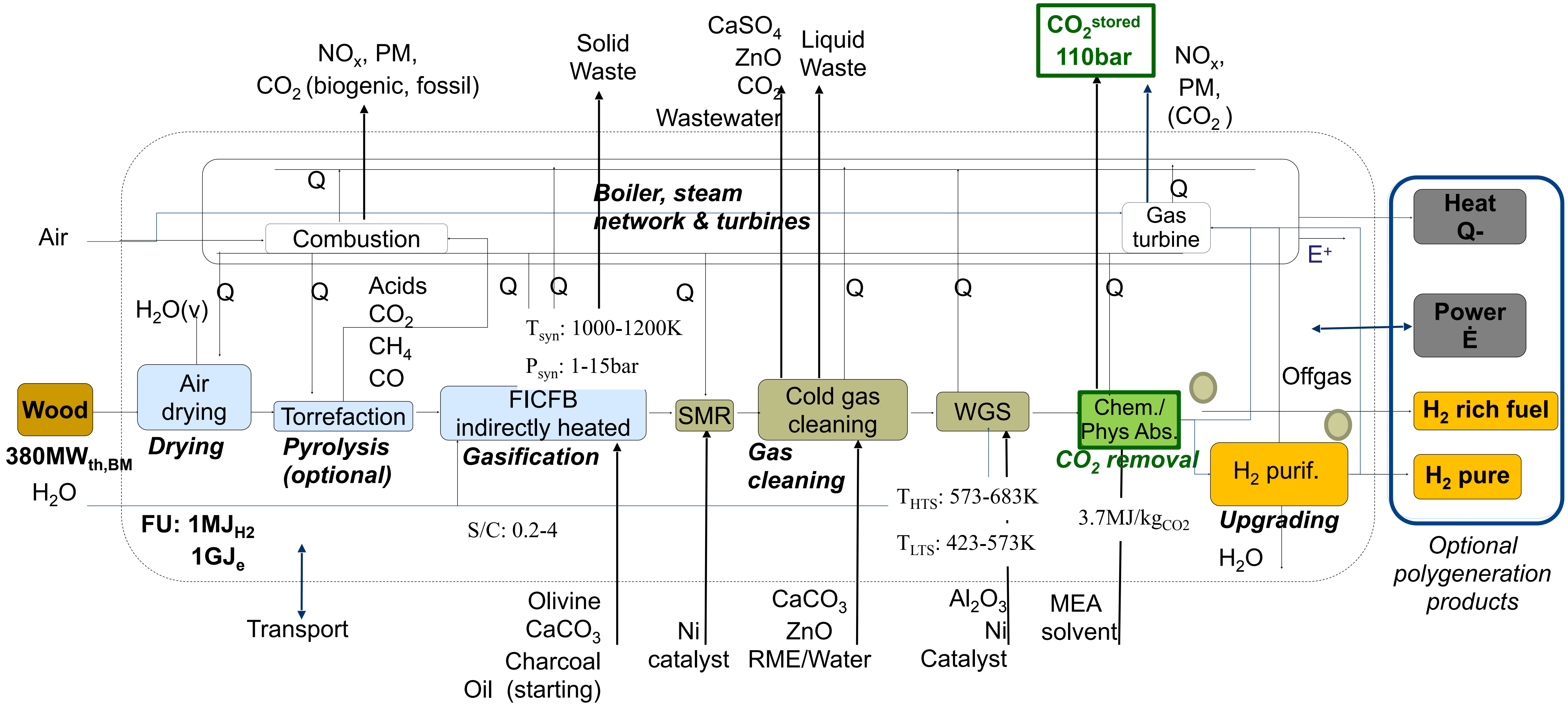
- Superstructure of pre-combustion processes[6]
  - Conceptual process design of fuel decarbonisation



$$\text{WGS}: \; CO + H_2O \xleftrightarrow{\Delta \tilde{h}_r^o = -41 kJ/mol} CO_2 + H_2$$

[6] Tock et al. IJHE 2012

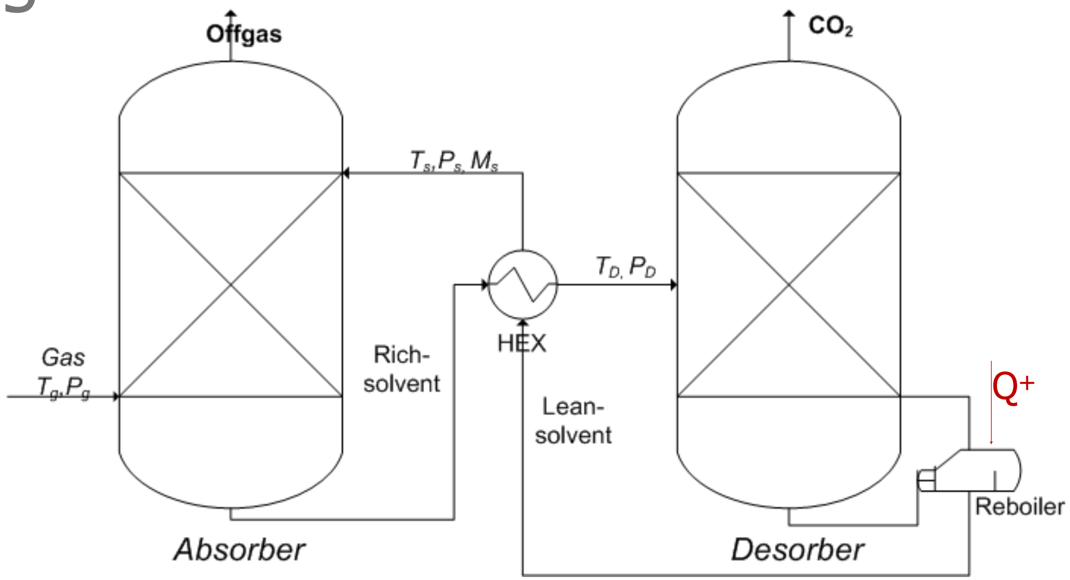
Electricity production with CO2 capture



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

Context

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



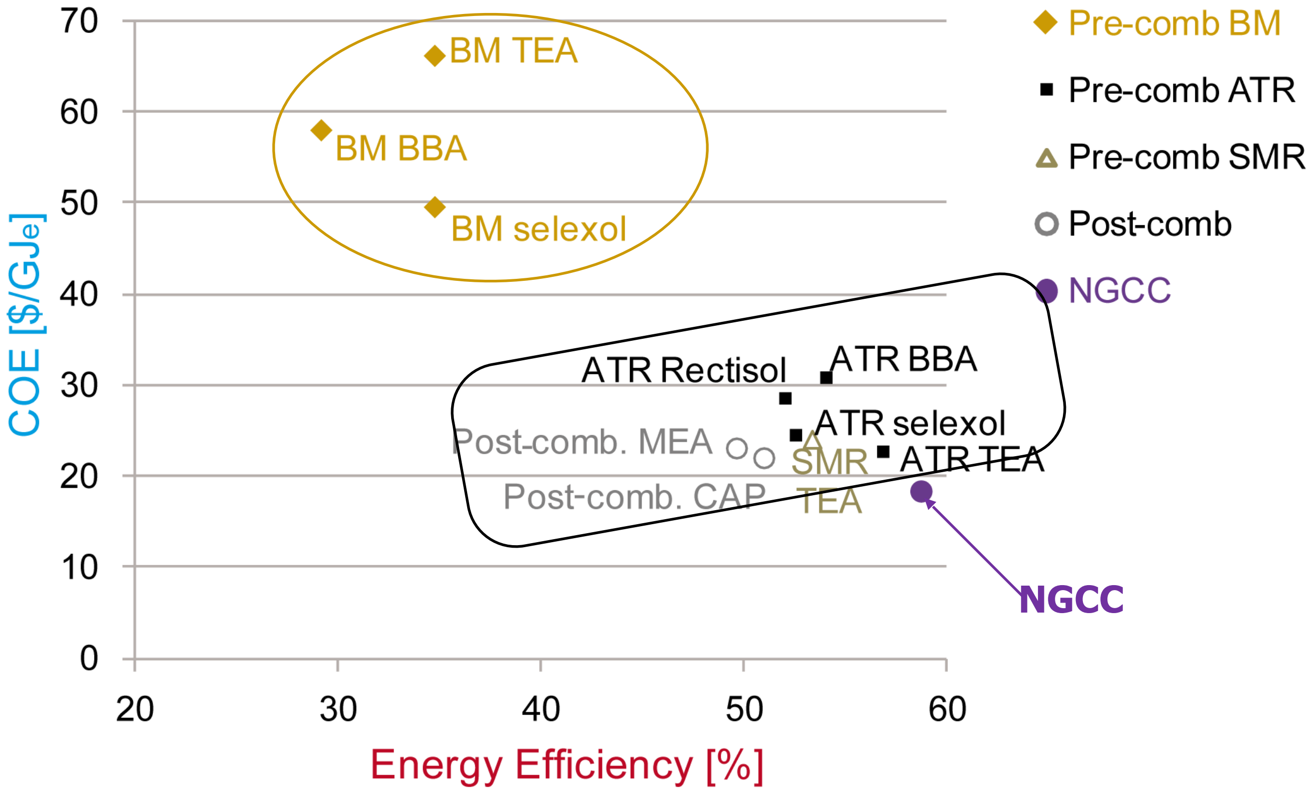
Operating conditions ? ***Separation/purification capacity ?*** ***Energy requirement ?*** ***Costs ?***

Process[2]	Conditions	Gas removed	Thermal energy [kWh/kg$_{CO2}$]	Mechanical work [kWh/kg$_{CO2}$]	CO_2 purity [%mol]
Rectisol	$T_{abs} \approx -10/-70^oC$ $p_{CO2} > 10$ bar	CO_2, NH_3 H_2S, COS, HCN	0.025	0.038	<90%
Selexol	$p_{CO2} \approx$7-30 bar	CO_2, NH_3 H_2S, COS, HCN	0.016-0.024	0.03-0.06	
MEA	$T_{abs} \approx 40^oC$, 1-5 bar $T_{desorb} = 95-120^oC$	CO_2, CS_2 H_2S, SO_2, COS	2.3 ($\approx$0.48kWh$_e$/kg$_{CO2}$)	0.05-0.3	< 99%
PSA-Flue gas 28-34% CO_2	P_{ads}=1 bar P_{desorb}=0.05-0.9 bar	CO_2	0.16-0.18		
PSA - syngas	P_{ads}=13-21 bar P_{desorb}<1 bar	CO_2			>90%

[2]Göttlicher 1999

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%

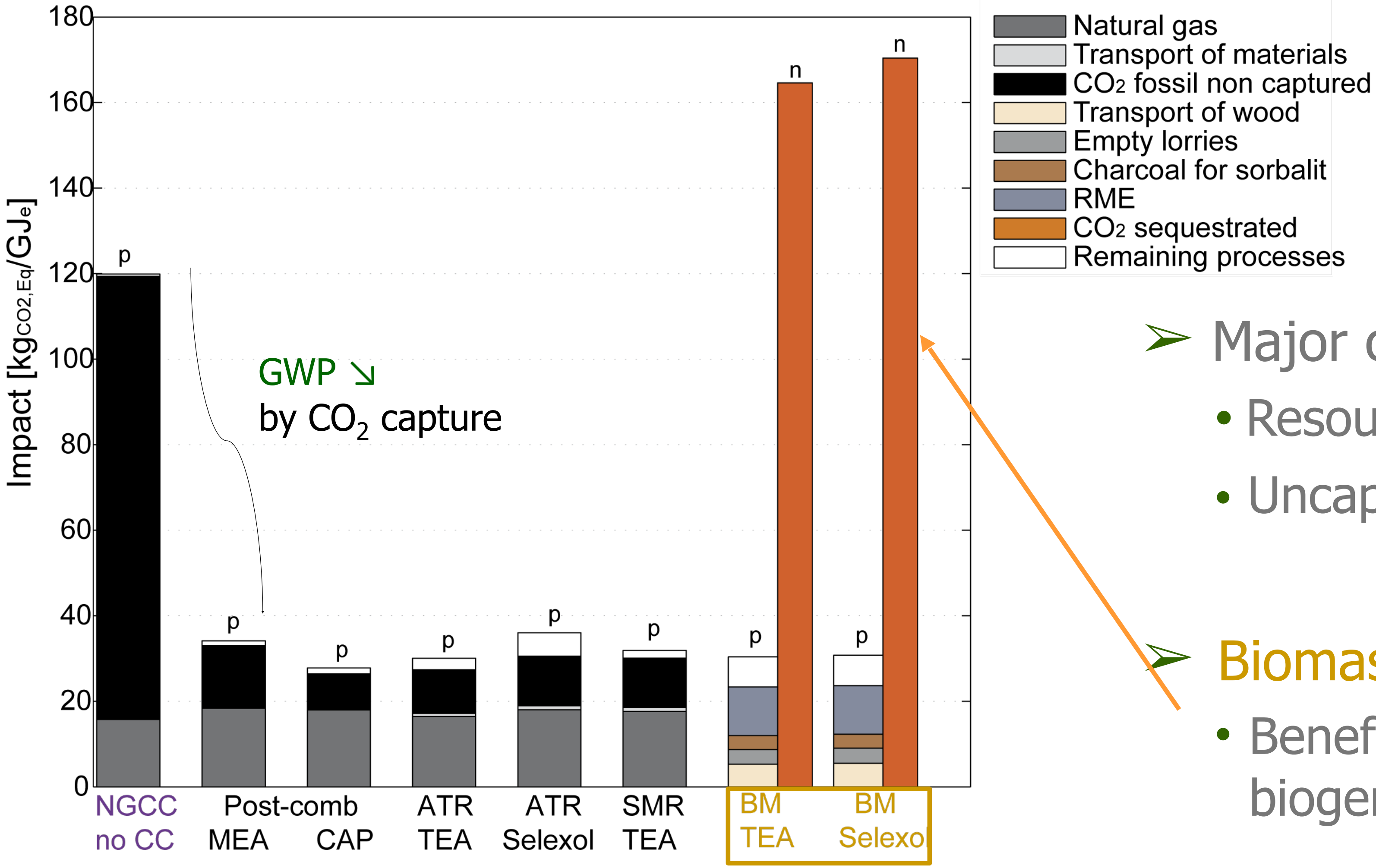


  - ➢ Competition between post- and pre-combustion

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

CO_2 capture options comparison

- CO_2 capture 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 !

Decision-making

- 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!

Producing electricity from biomass

- efficiency <40% : Combustion + Rankine cycle => cogeneration
- efficiency up to 70% : Gasification +
  - Gas turbines
  - Engines
  - Fuel cells + Rankine cycle
- efficiency 40% : Gasification + Reforming
  - H2 production
  - CO2 separation for sequestration