Thermochemical conversion of biomass

François Maréchal

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

Photosynthesis

Ingredients	*Product*
Sunlight +	
$H_2O + CO_2$ + Nutrients →	"CH_2O" + O_2

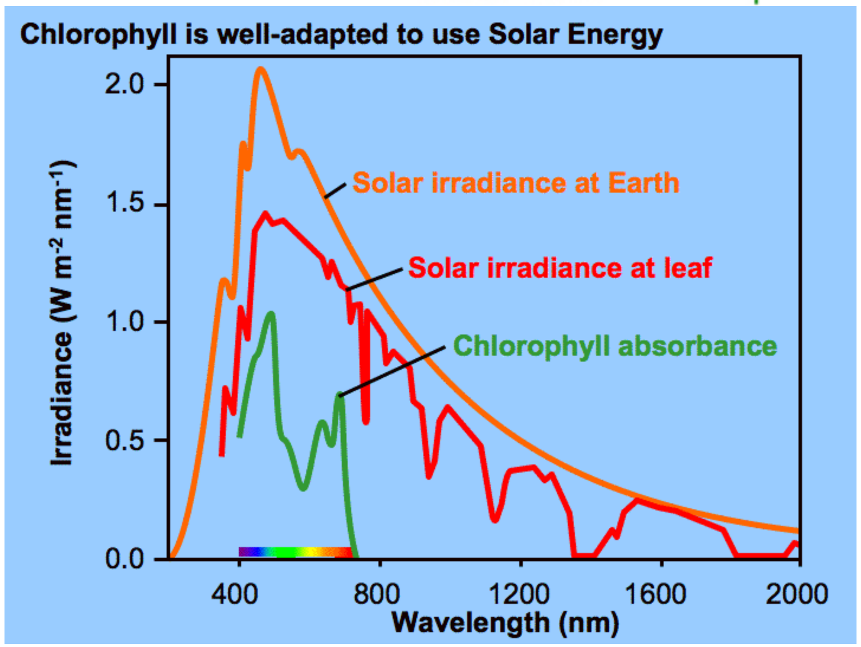
Water

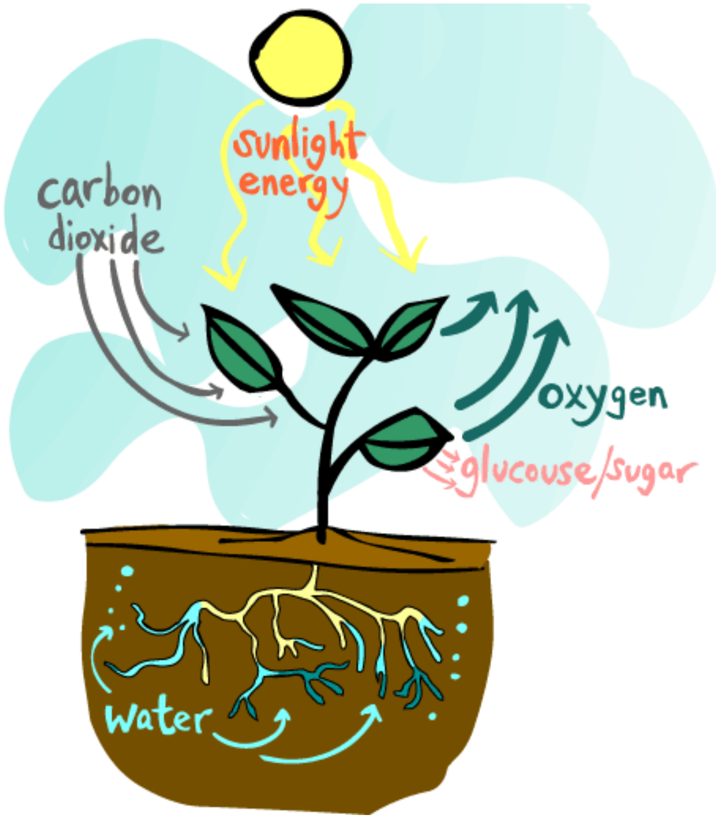
Carbon dioxide

Nitrate NO_3
Phosphate PO_4
Iron
Silica
among others

"Organic matter"

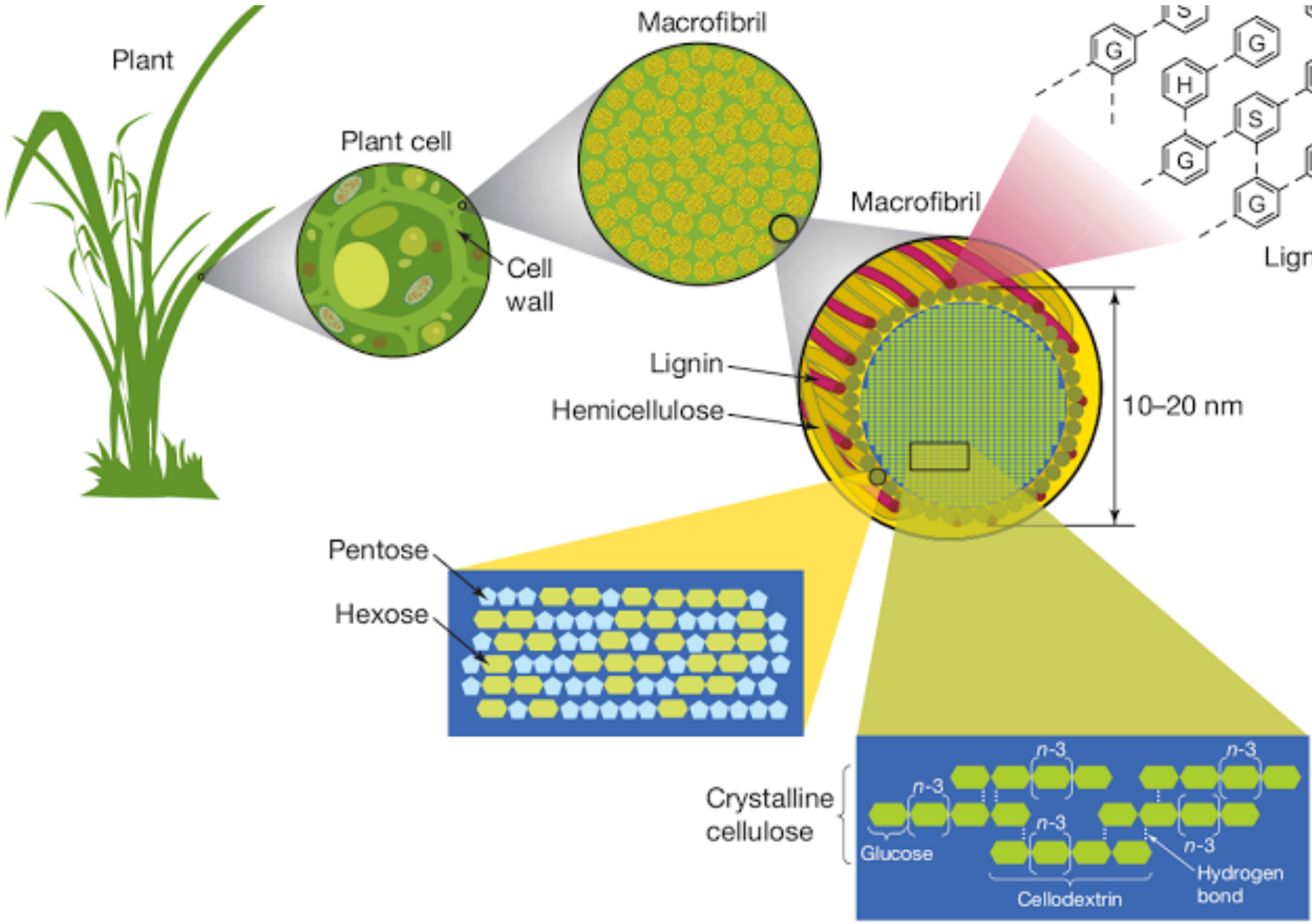
Oxygen





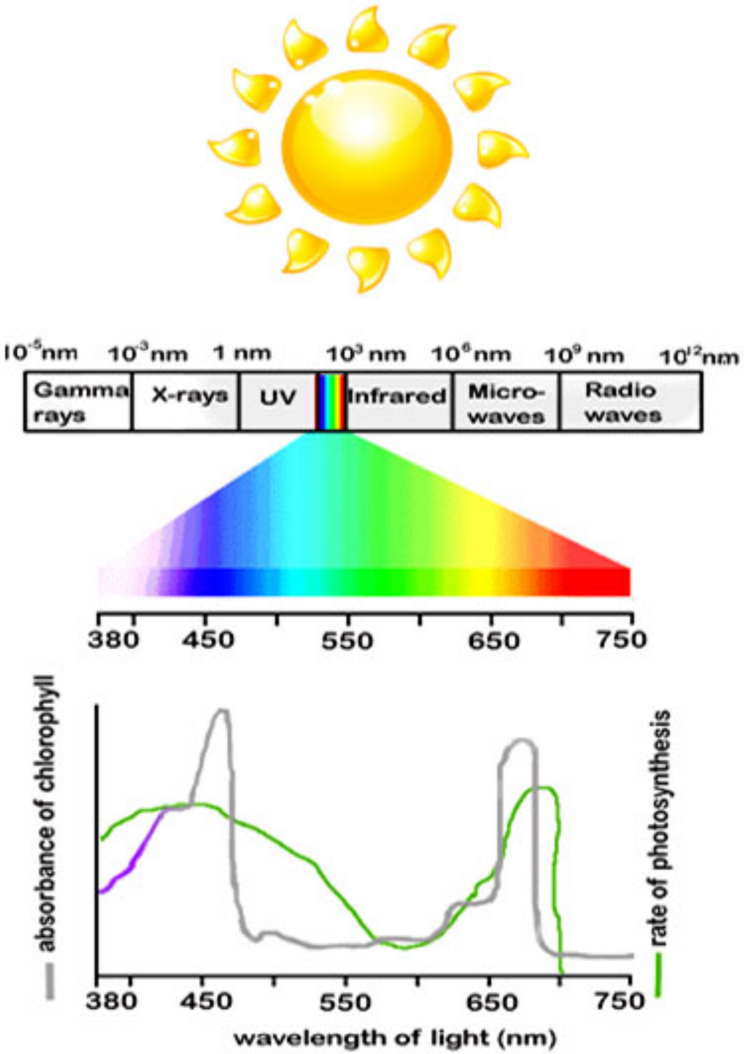
Source: http://www.sheppardsoftware.com

Lignocellulosic Biomass Characterization



Source: Peduzzi. Biomass Conversion Lecture EPFL 2012.

Photosynthetis Efficiency



Photosynthetically active light from the Sun:
Only 45% available

↓

Maximum theoretical photosynthetic efficiency (25%):
Only 11% available

↓

Losses due to reflection, conversion inefficiencies etc…
Only 3-6% of the sunlight's energy is useable by plants

↓

20-40% of energy exuded into the soil to feed the microbes:
1-3%

Only 1-3% of the energy from sunlight is utilized by plants

Source: http://www.greenearthagandturf.com/

Biomass production

Solar radiation : $5.5\ 10^{24}$ J

$2.6\ 10^{24}$ J absorption and reflection

$5.1\ 10^{23}$ J (cultivable area)

$5.1\ 10^{21}$ J (photosynthesis efficiency)

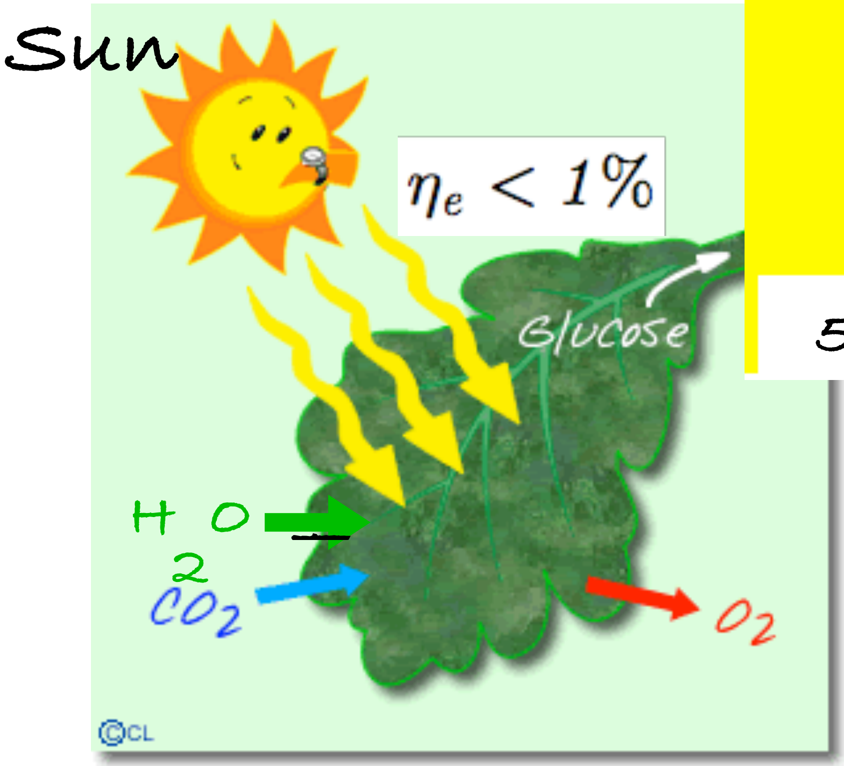
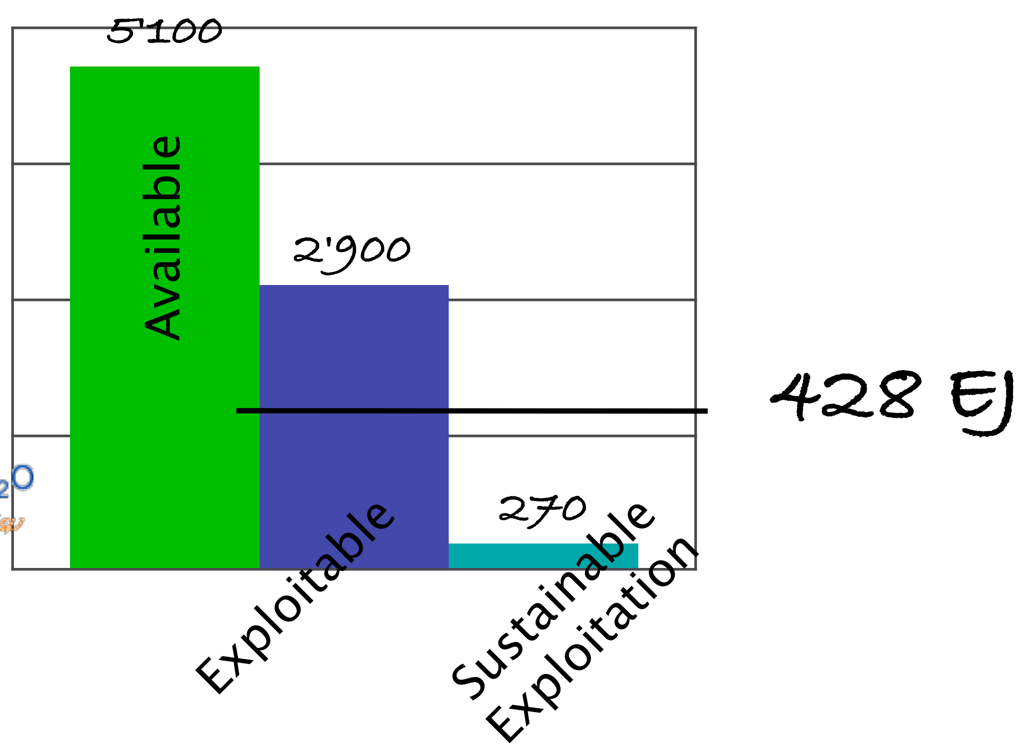


Schéma de la photosynthèse

$6\ CO_2$ + $12\ H_2O$ + énergie lumineuse $\longrightarrow$ $C_6H_{12}O_6$ + $6\ O_2$ + H_2O

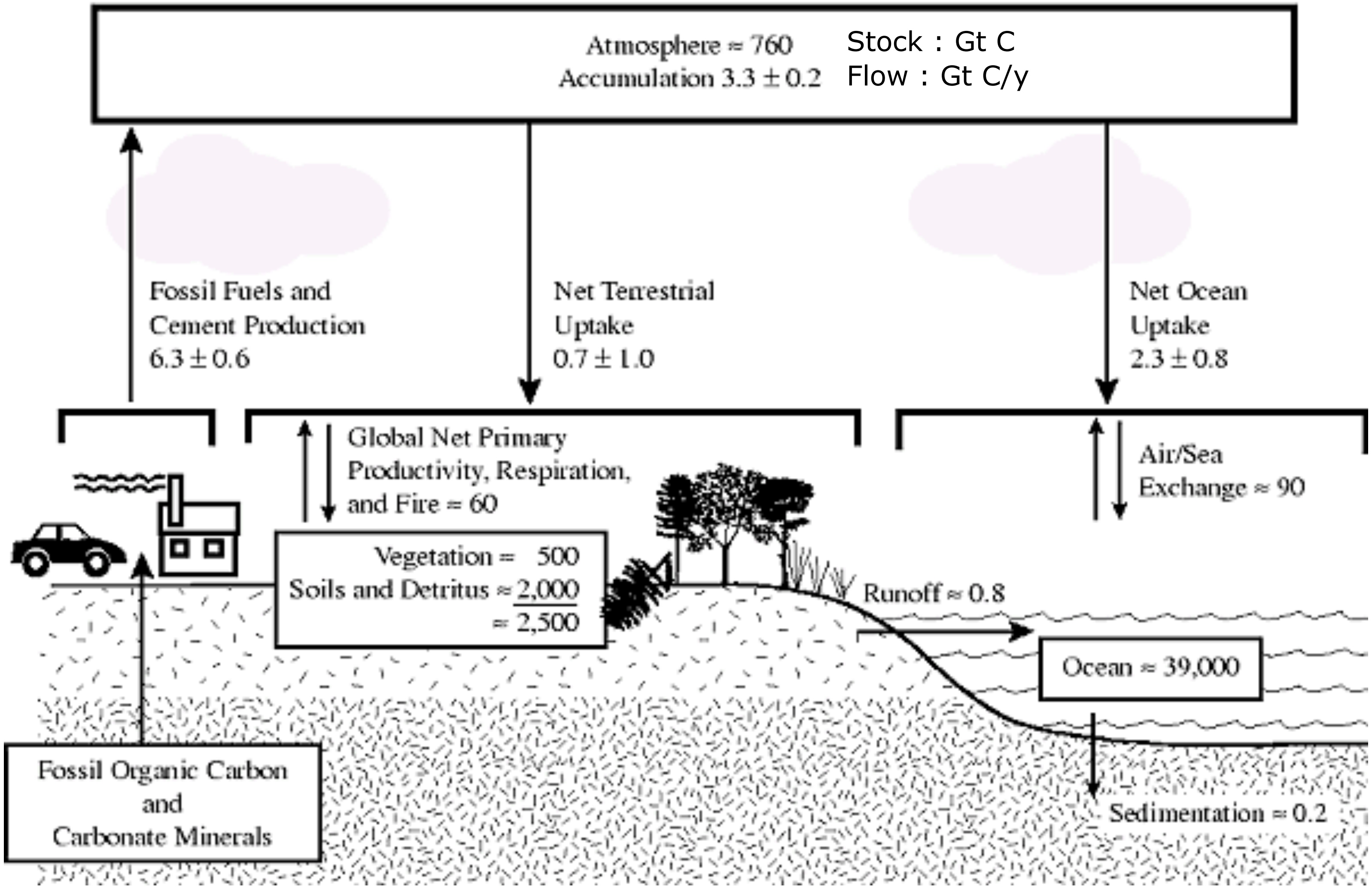
Dioxyde de carbone — Eau — Glucose — Oxygène — Eau

Equation de la photosynthèse



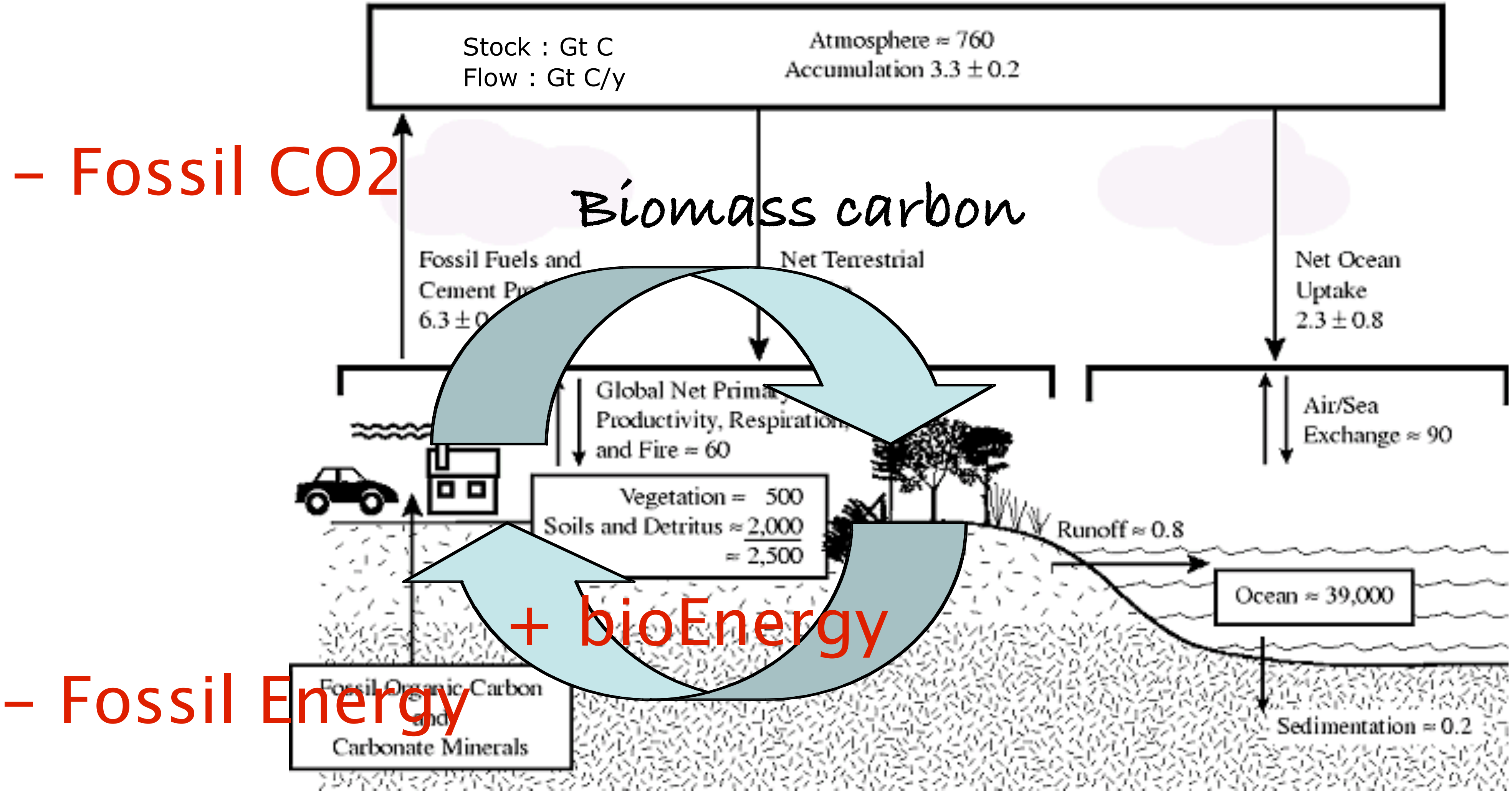
crédits : www.ucl.ac.be

CO2 cycle



Atmosphere ≈ 760
Accumulation 3.3 ± 0.2
Stock : Gt C
Flow : Gt C/y
Fossil Fuels and
Cement Production
6.3 ± 0.6
Net Terrestrial
Uptake
0.7 ± 1.0
Net Ocean
Uptake
2.3 ± 0.8
Global Net Primary
Productivity, Respiration,
and Fire ≈ 60
Air/Sea
Exchange ≈ 90
Vegetation ≈ 500
Soils and Detritus ≈ 2,000
≈ 2,500
Runoff ≈ 0.8
Ocean ≈ 39,000
Sedimentation ≈ 0.2
Fossil Organic Carbon
and
Carbonate Minerals

CO2 cycle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Global Net Prima
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and Fire ≈ 60
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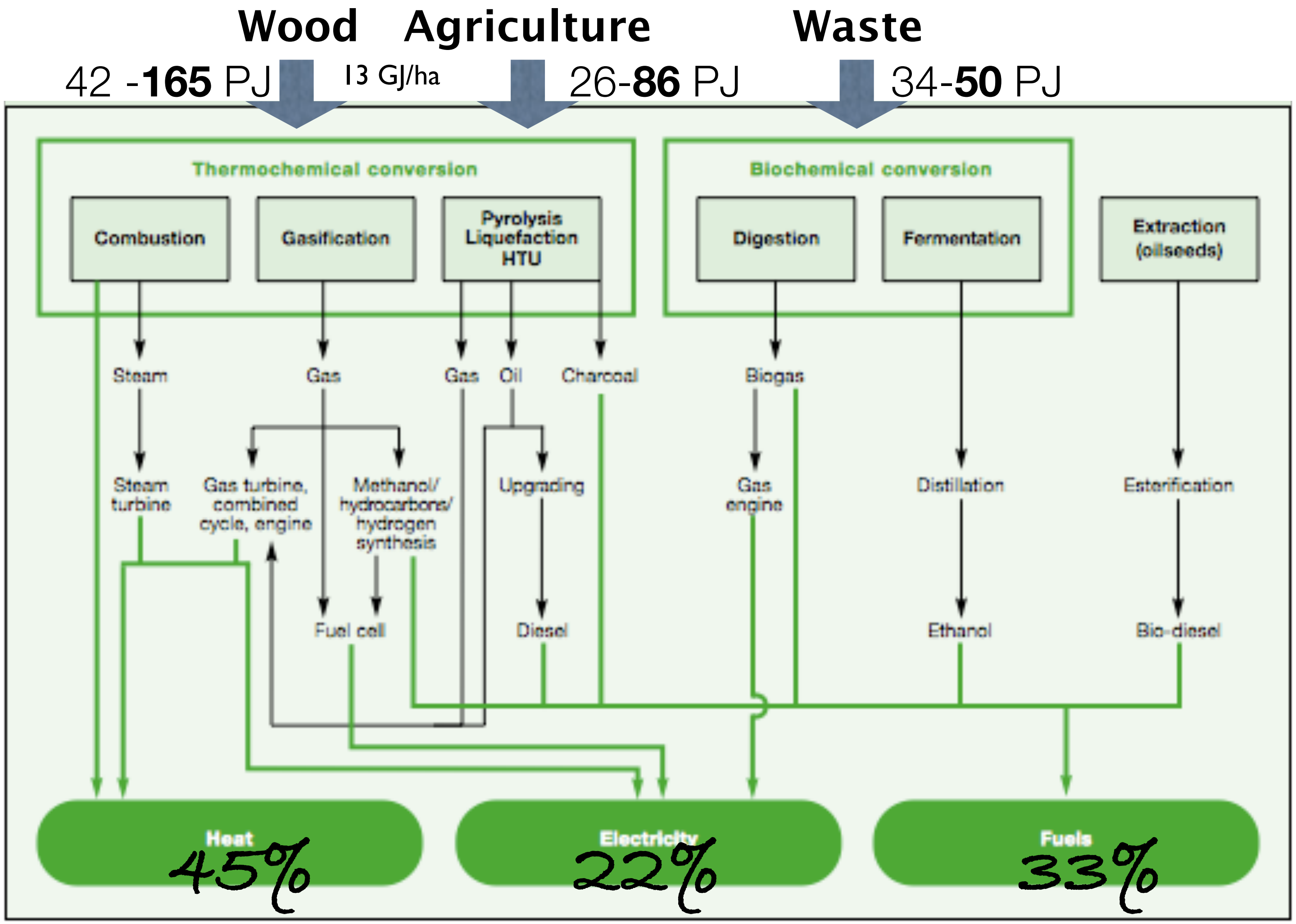
Soils and Detritus ≈ 2,000
≈ 2,500
Runoff ≈ 0.8
Ocean ≈ 39,000
+ bioEnergy
- Fossil Energy
Carbonate Minerals
Sedimentation ≈ 0.2

Biomass potential and conversion

Biomass production potential in Switzerland

sustainable -**Technical** in PJ/year



Figures for Switzerland (sustainable potential : total = 82-301 PJ)

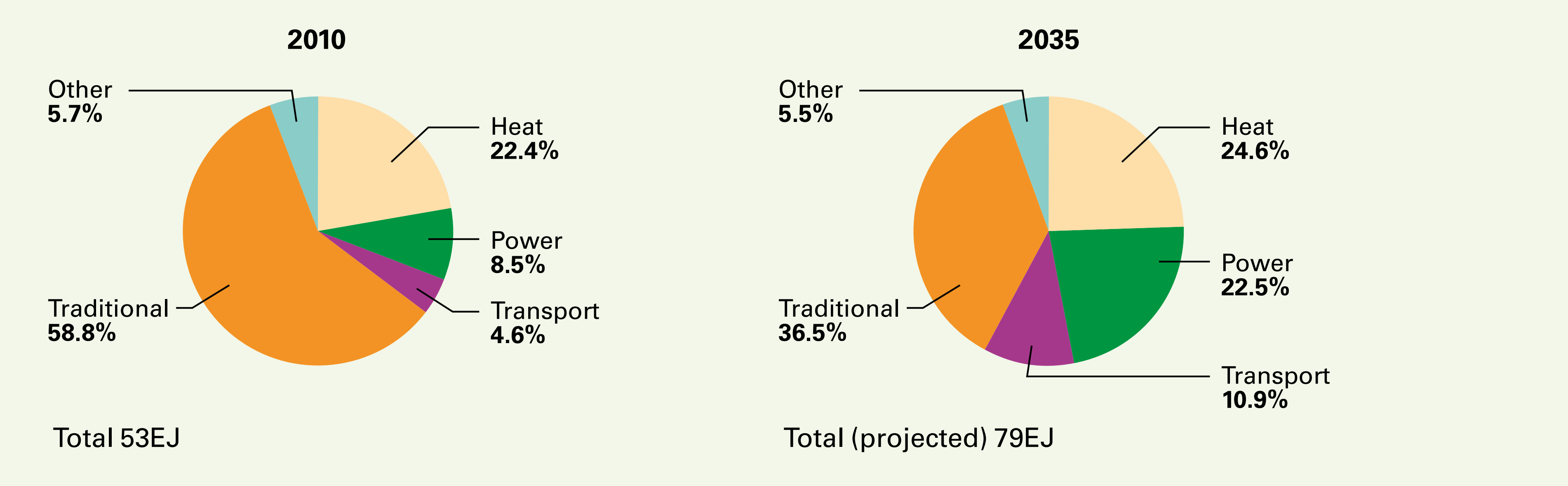
Source : world energy assessment : UNDP 2000

Bioenergy in Switzerland: assessing the domestic sustainable biomass potential
B Steubing, R Zah, P Waeger, C Ludwig
Renewable and Sustainable Energy Reviews 14 (8), 2256-2265

Bioenergy usage : projections

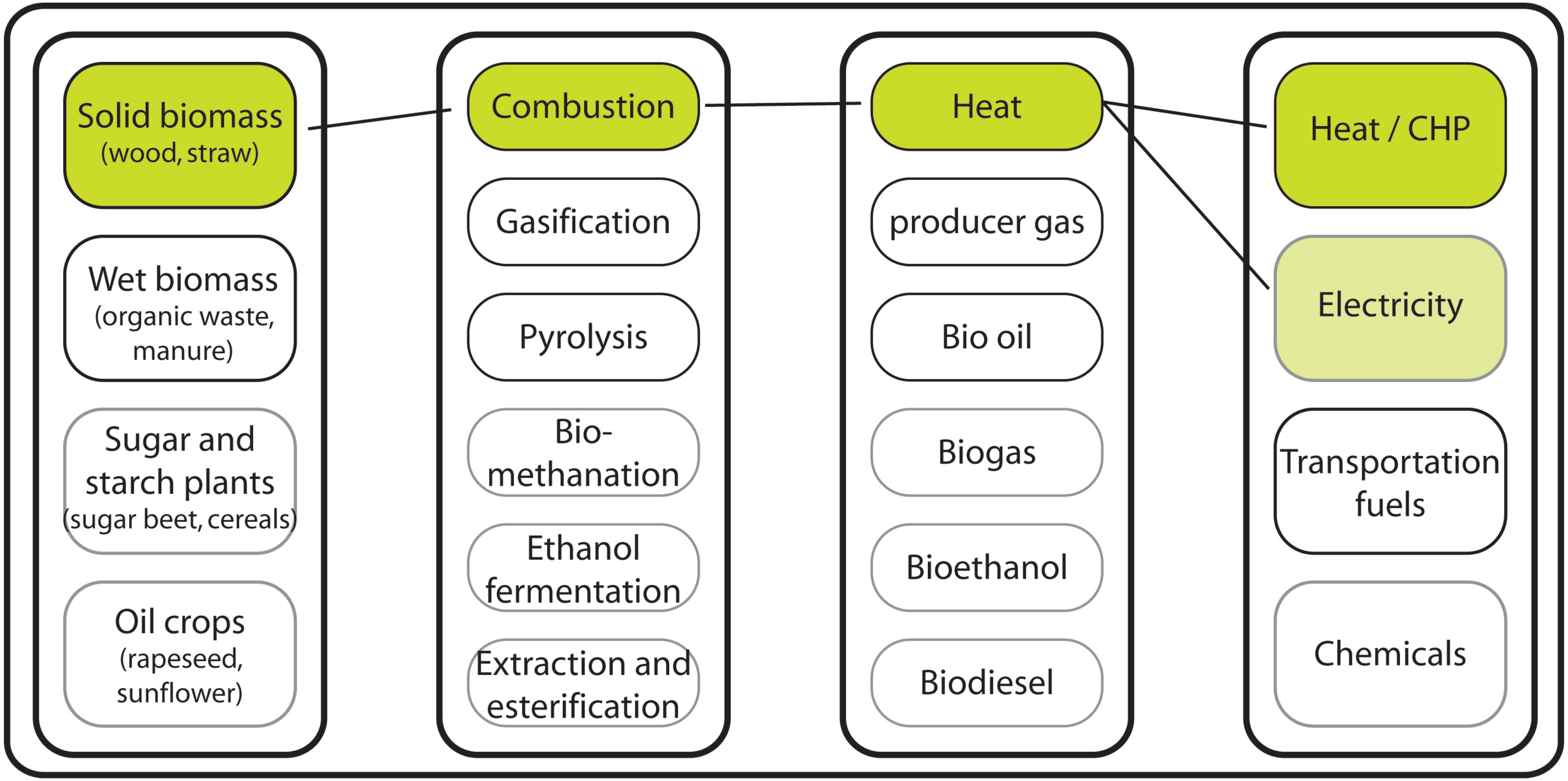
Figure 1.5

Use of bioenergy by sector in 2010 and 2035 (projected by the IEA for conditions where new policies are implemented). Use is estimated to rise from 53EJ in 2010 to 79EJ in 2035. The proportion used for heat by traditional methods (heating and cooking) is projected to fall considerably; the proportion used for heat via modern methods of production remains almost unchanged; while proportions used for power and transport by modern methods make significant increases[2].



Davis, S.C., Hay, W. & Pierce, J. (2014),
Biomass in the energy industry: an introduction.

Biomass conversion
Combustion



adapted from Chemical Engineering 10 (2006)

Heating value of biomass

- **Higher heating value (MJ/kg_{dry})**
  - Boie formula

$$HHV = 35.17 c_C + 116.26 c_H - 11.10 c_O + 10.47 C_S + 6.28 c_N$$

  - concentrations in (%mass)

- **Lower heating value (MJ/kg_{dry})**

$$LHV_{dry} = HHV - \frac{\tilde{m}_{H2O}}{2} c_H * \Delta h_{vap}$$

$$LHV_{wet} = HHV - (\frac{\tilde{m}_{H2O}}{2} c_H + \frac{\phi}{1-\phi}) * \Delta h_{vap}$$

$$\phi \quad in \quad \% mass \qquad \Delta h_{vap} = 2441 [kJ/kg]$$

Typical heating value

substance name	ID in [4]	humidity[1]	C	H	O	N	S	ash	HHV	LHV_{dry}
		%wt	%wt						MJ/kg_{dry}	MJ/kg_{dry}
municipal solid waste	1518	39	31.0	1.0	21.6	1.1	0.8	44.5	9.7	9.3
wet sewage sludge	2810	73	27.0	3.8	17.2	3.2	0.9	47.8	12.3	10.7
freshwater biomass	2319	84	54.6	6.7	23.4	6.7	0.4	8.2	24.9	23.3
fruit/vegetable waste	**2811**	**7**	**46.5**	**6.1**	**38.5**	**0.7**	**0.5**	**7.7**	**19.2**	**17.8**
cattle manure	**1885**	**13**	**13.0**	**1.5**	**10.1**	**1.5**	**0.3**	**73.6**	**5.3**	**4.1**
pig manure	**1366**	**92**	**35.4**	**4.5**	**21.5**	**2.8**		**35.8**	**15.2**	**13.7**
poultry manure	1872	4	35.9	5.0	27.4	3.6	0.8	27.4	15.7	14.2
sugarbeet	417	77	44.5	5.9	42.8	1.8	0.1	4.8	17.9	16.5
bagasse	894	10	48.6	5.9	42.8	0.2		2.4	19.2	17.9
grass	568	40	48.0	5.5	41.1	0.5	0.1	4.8	18.7	17.5
vine shoots	1253		46.9	5.9	44.2	0.8		2.2	18.4	17.1
straw	**2129**	**14**	**47.7**	**5.9**	**41.0**	**0.7**	**0.2**	**4.5**	**19.1**	**17.7**
wood	own data	50	50.7	5.7	42.7	0.2		0.7	19.8	18.5
lignin	2000	75	62.1	5.9	31.1	0.2	0.1	0.6	25.3	24.0
rapeseed	2156	5	58.7	8.6	23.5	3.7		5.5	28.3	26.3

[4] Phyllis, database for biomass and waste. Energy research center of the Netherlands, http://ecn.nl/phyllis.

Compared with other fuels

	HHV [MJ/kg]	LHV [MJ/kg]
Hydrogen	141.8	121
Methane	55.5	50
Gasoline	47.3	44.4
Paraffin	46	41.5
Kerosene	46.2	43
Diesel	44.8	43.4
Coal (Anthracite)	27	
Coal (Lignite)	15	
Wood (MAF)	21.7	

Wiki

Energy Densities of Various Fuels

Fuel	Particle Density	Bulk Density	Energy Density
	kg/m^3	kg/m^3	GJ/m^3 bulk product
Crude oil		855	35.8
Coal	1350	700	21
Natural gas (80 bar)		57	2.9
Biomass	450	230	3.7
Bio-oil		1200	20
Gasoline		760	35
Methanol		784	19

Source: Higgman

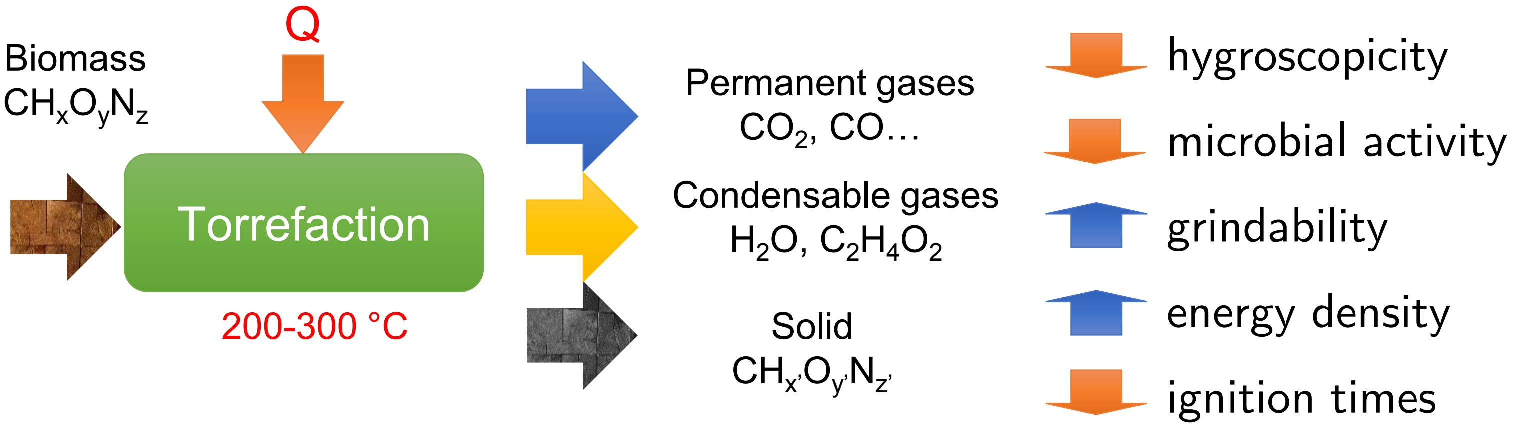
	Proximate Analysis [% by wt dry basis]			Ultimate Analysis [% by wt dry basis]					HHV [MJ/kg_{db}]
	FC	VM	ASH	C	H	O	N	S	
Coal - 8 Anth	84.59	7.09	8.32	83.67	3.56	2.84	0.55	1.05	32.856
Woodchips	23.5	76.4	0.1	48.1	5.99	45.74	0.08	0	19.916
Eucalyptus	21.3	75.35	3.35	46.04	5.82	44.49	0.3	0	18.64
Wheat straw	23.5	63	13.5	45.5	5.1	34.1	1.8	–	17
Miscanthus	12.4	87.2	0.4	–	–	–	–	–	19.297

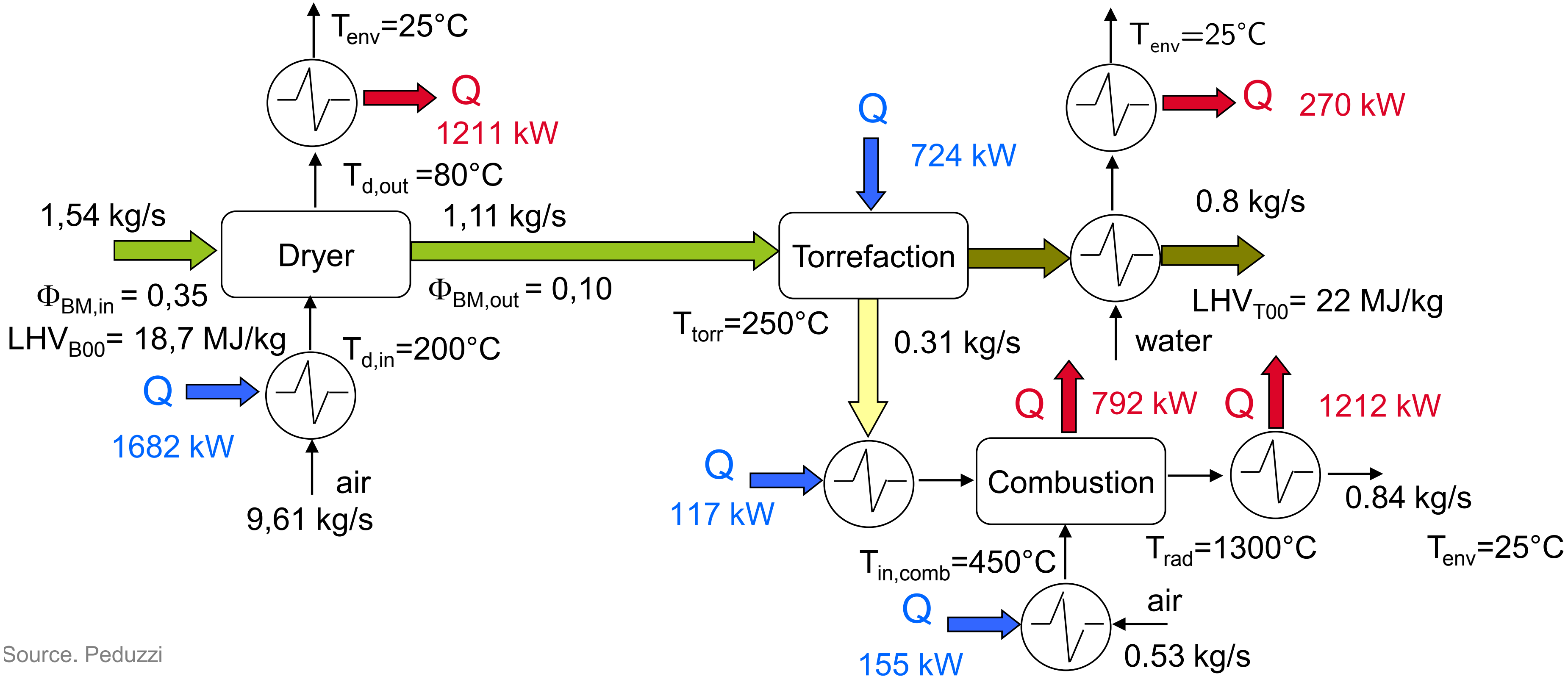
Parikh 2005

Compared to other resources

		Natural gas	Wood	Gasoline	Diesel
	kg/m3	700	240	800	800
LHV	MJ/kg	50	17.8	44.4	43.4
	GJ/Nm3	0.0359	5.3-9.6	35.5	34.7
CO2	g CO2/MJ	49.3	0	67	72
supply eq CO2	g CO2/MJ	11.6	1.4-1.8 (production) 0.19 (20 MW) -1.1(320 MW) 1.6 - 2.9	16.7	13.4
	g CO2/MJ	60.9	1.6-2.9	83.7	85.4
		19%	-	20%	16%
Cost	cts/kWh	10	3 - 7.5	18.6	19.2
industry	cts/kWh	3.4			

Torrefaction : Increase the energy density/reduce the humidity

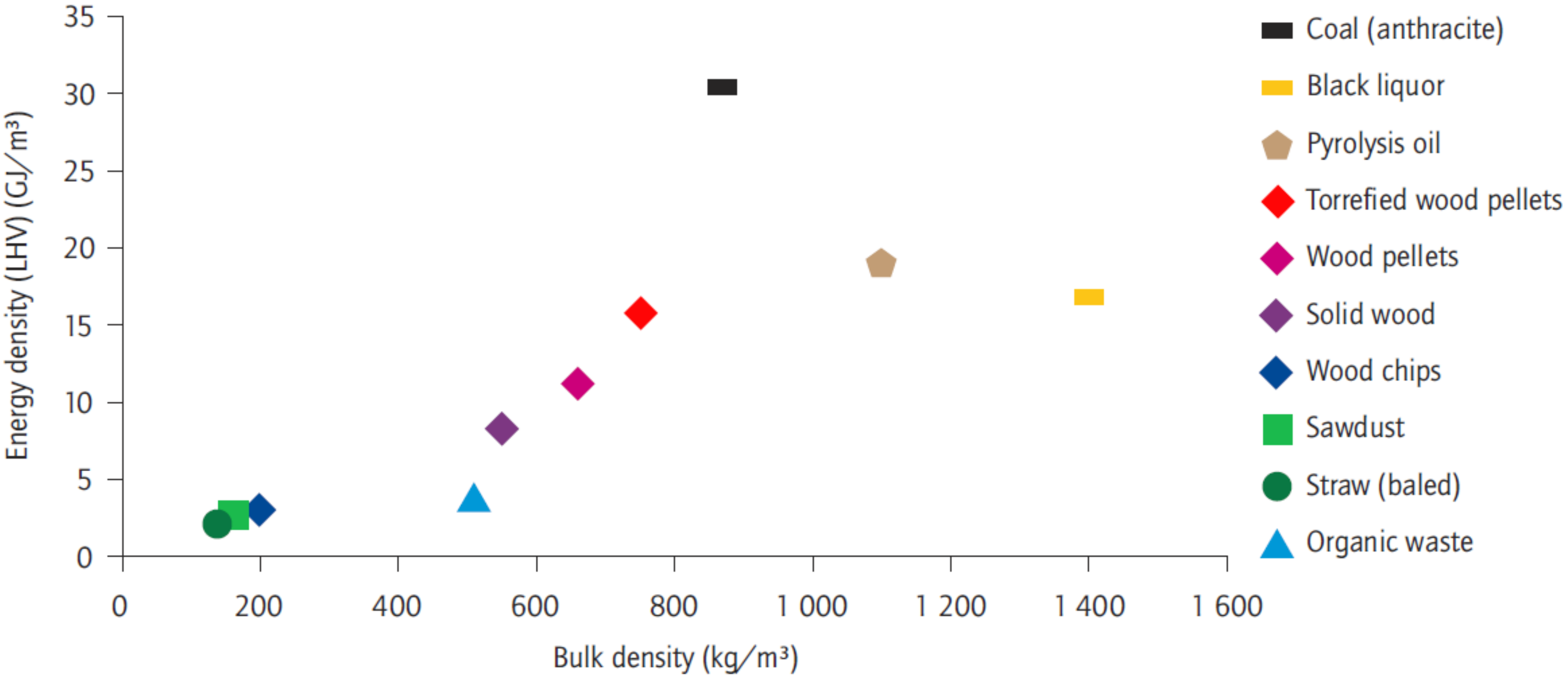




Source. Peduzzi

Energy density

Figure 5: Comparison of bulk density and energy density of different biomass feedstocks

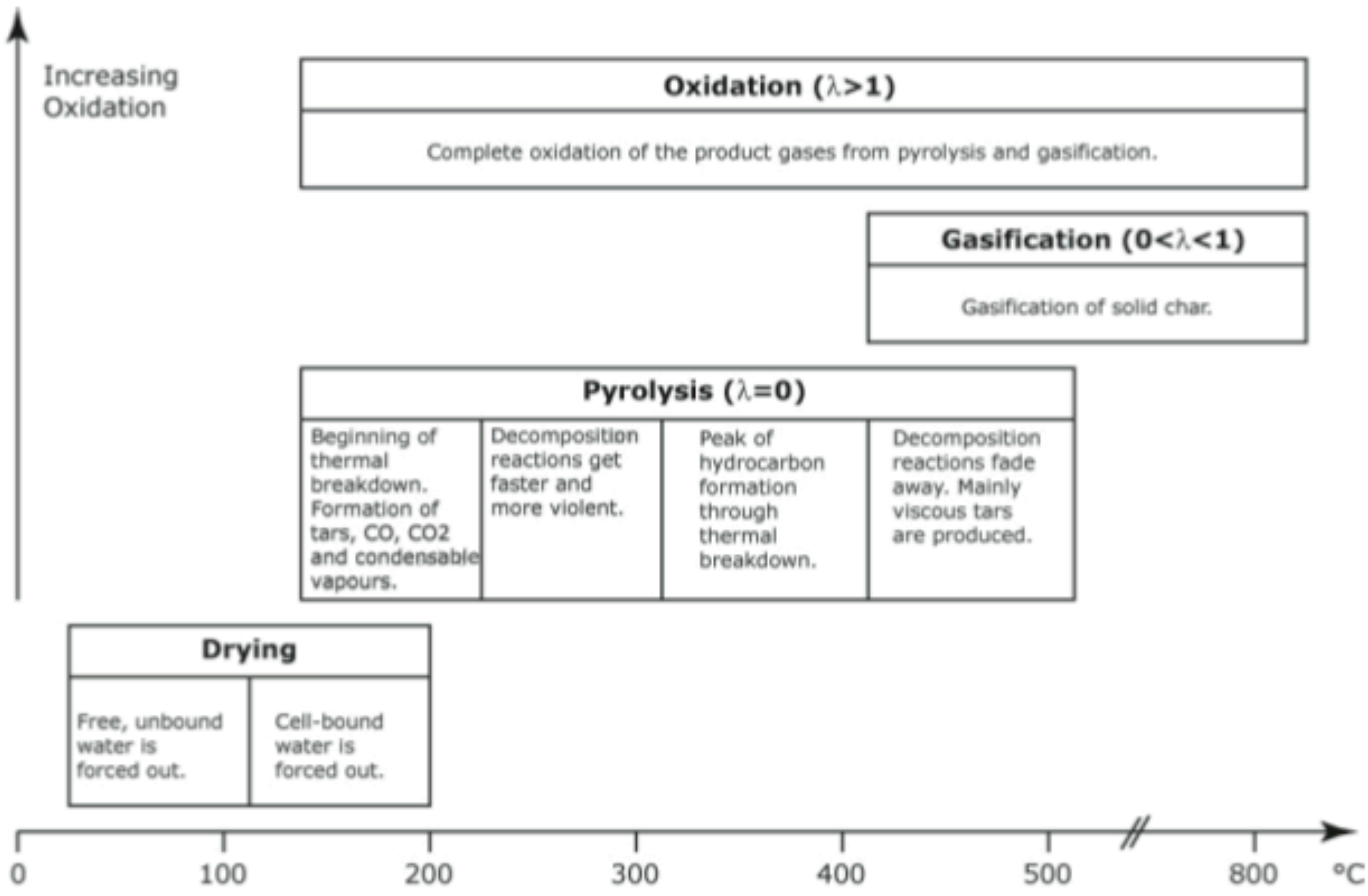


Source: IEA analysis based on DENA, 2011; FNR, 2011a; IEA Bioenergy, 2011; Kankkunen and Miikkulainen, 2003. For detailed data see Table 6 in Appendix I.

Source: IEA Technology Roadmape Bioenergy for Heat and Power, 2012.

Thermochemical biomass conversion

Process principles: gasification vs. pyrolysis

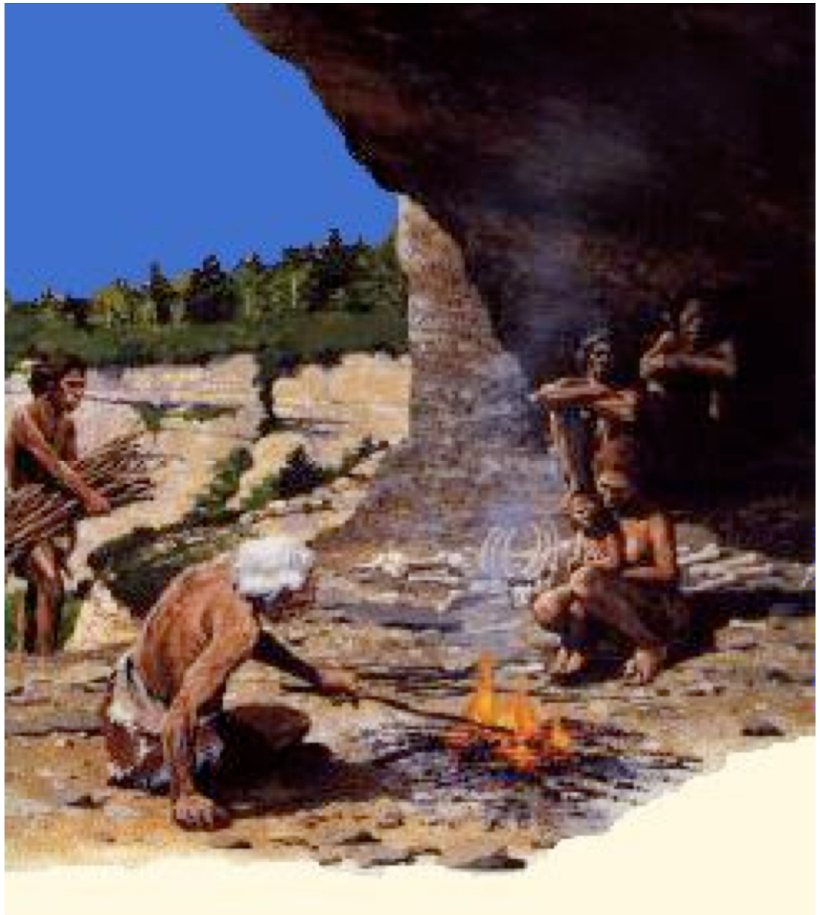


Combustion

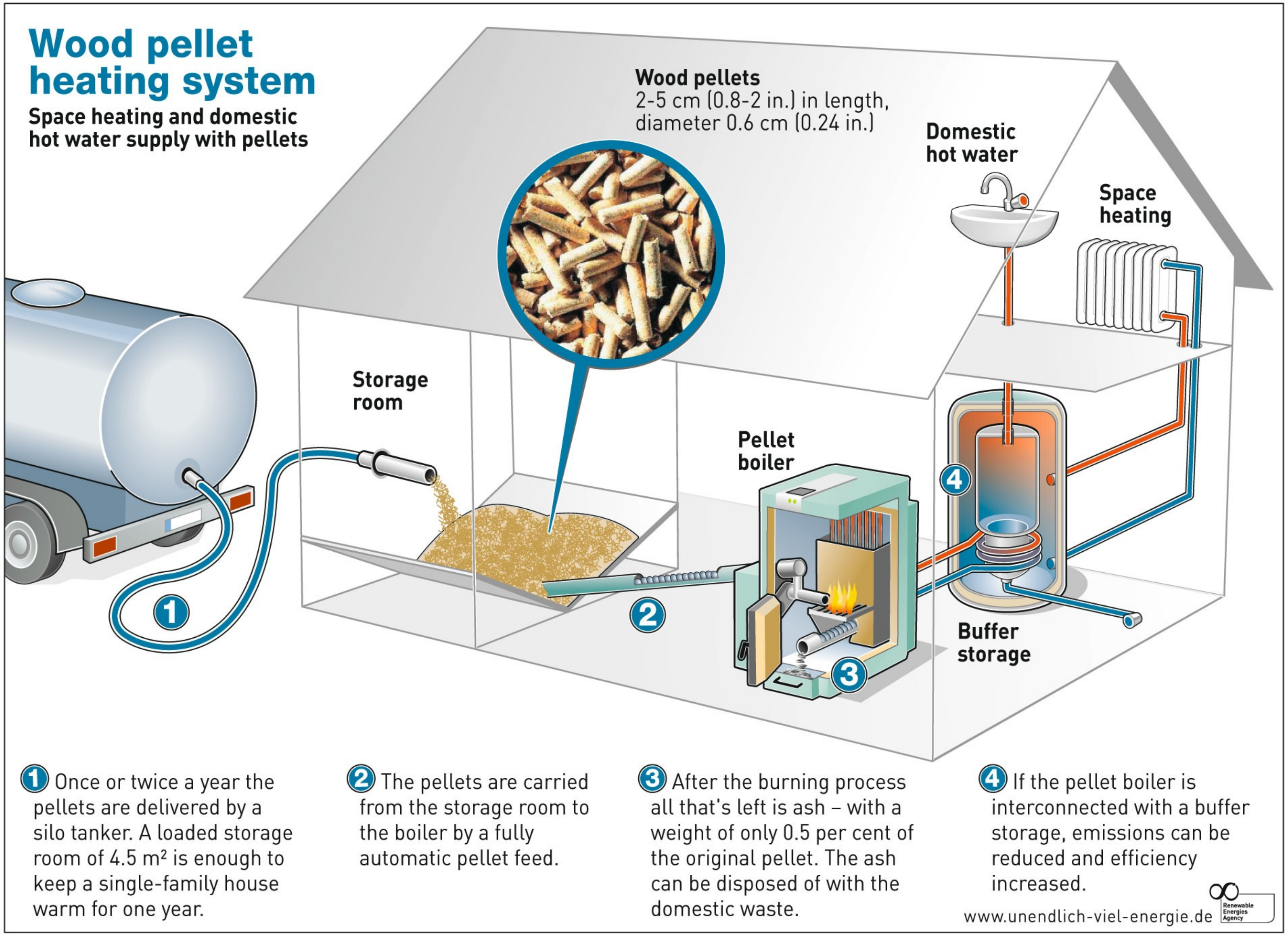
Known since more
than 400.000 years

1er law efficiency : 92% (LHV)
2nd law efficiency : 16% (T = 60°C)

Applications today
Domestic heating
District heating
Heat networks

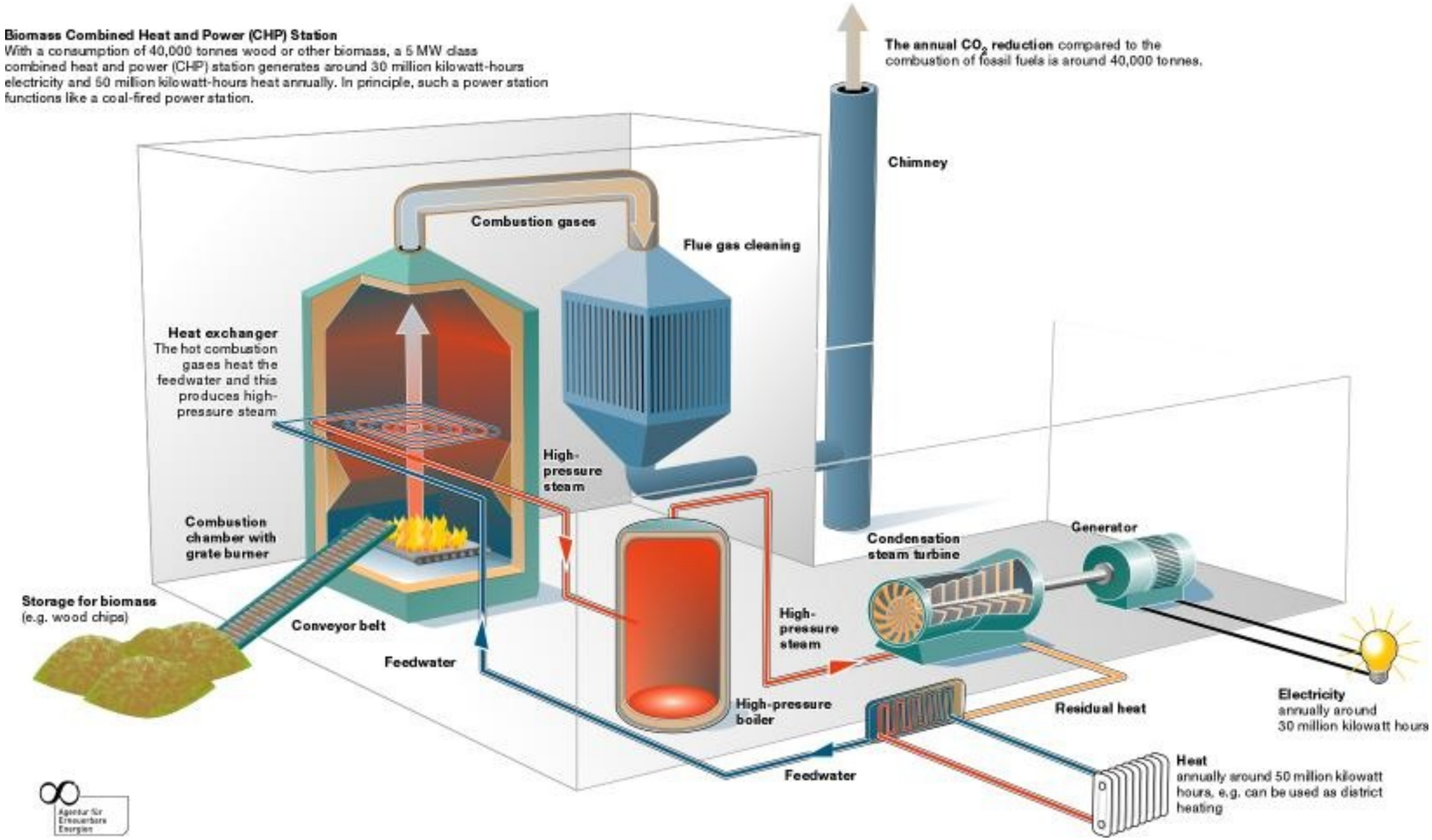


Biomass Combustion – Domestic Heating



http://www.unendlich-viel-energie.de/

Biomass CHP – Steam Cycle



http://www.unendlich-viel-energie.de/

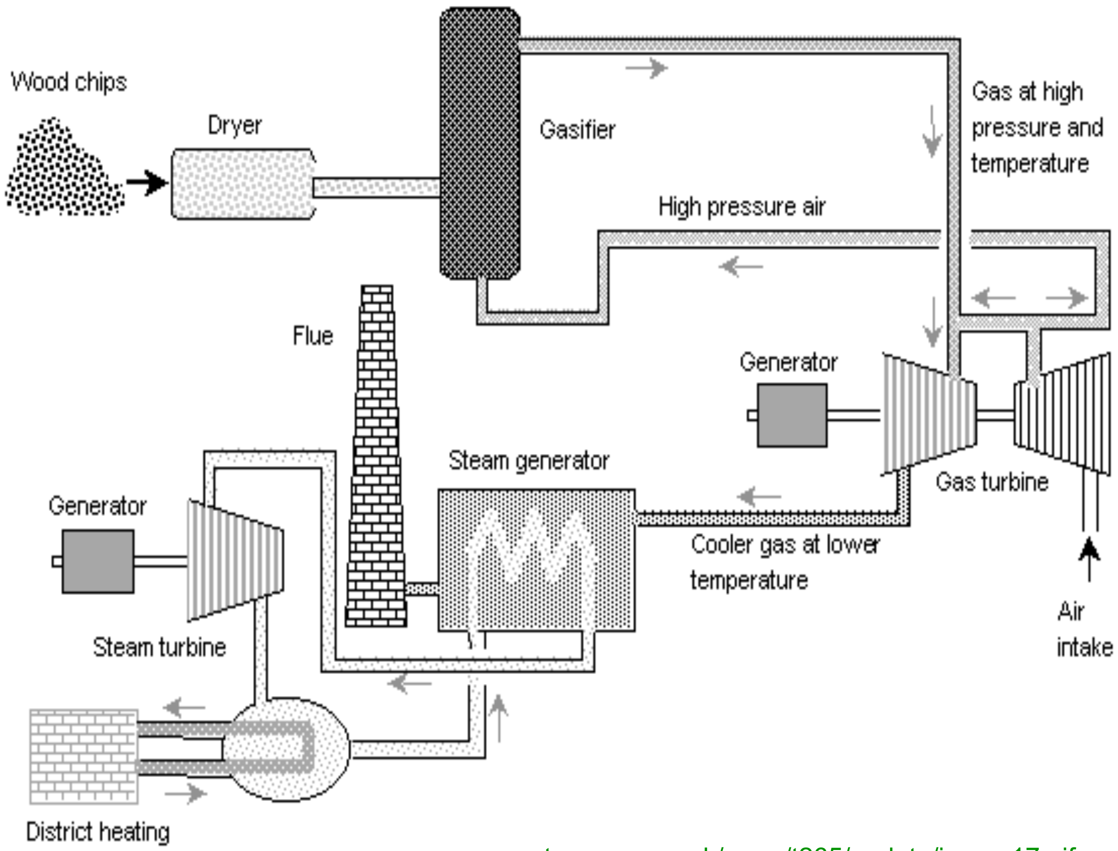
Combined heat and power

- **BIGCC Biomass Integrated gasification combined cycle**

Ressource
18.3 MW

Electricity
6. MW

Heat
9. MW



www-tec.open.ac.uk/ eeru/t265/update/image17.gif

Varnamo (SE) – 6 MWe (32%) /9 MWth plant

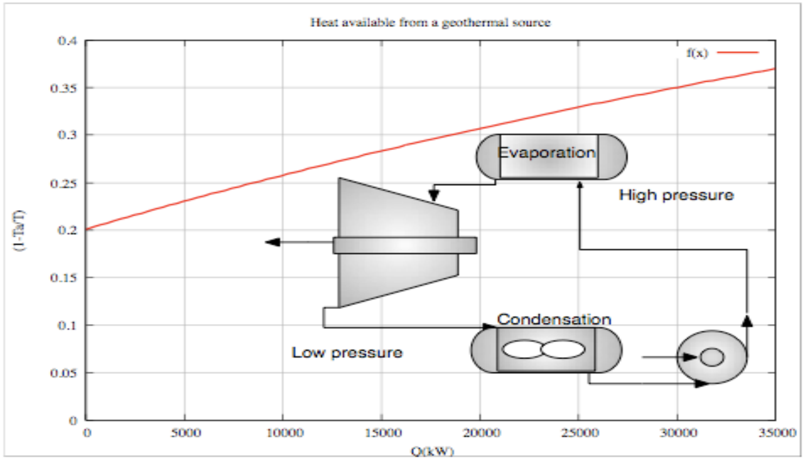
Cogeneration : ORC

IPESE

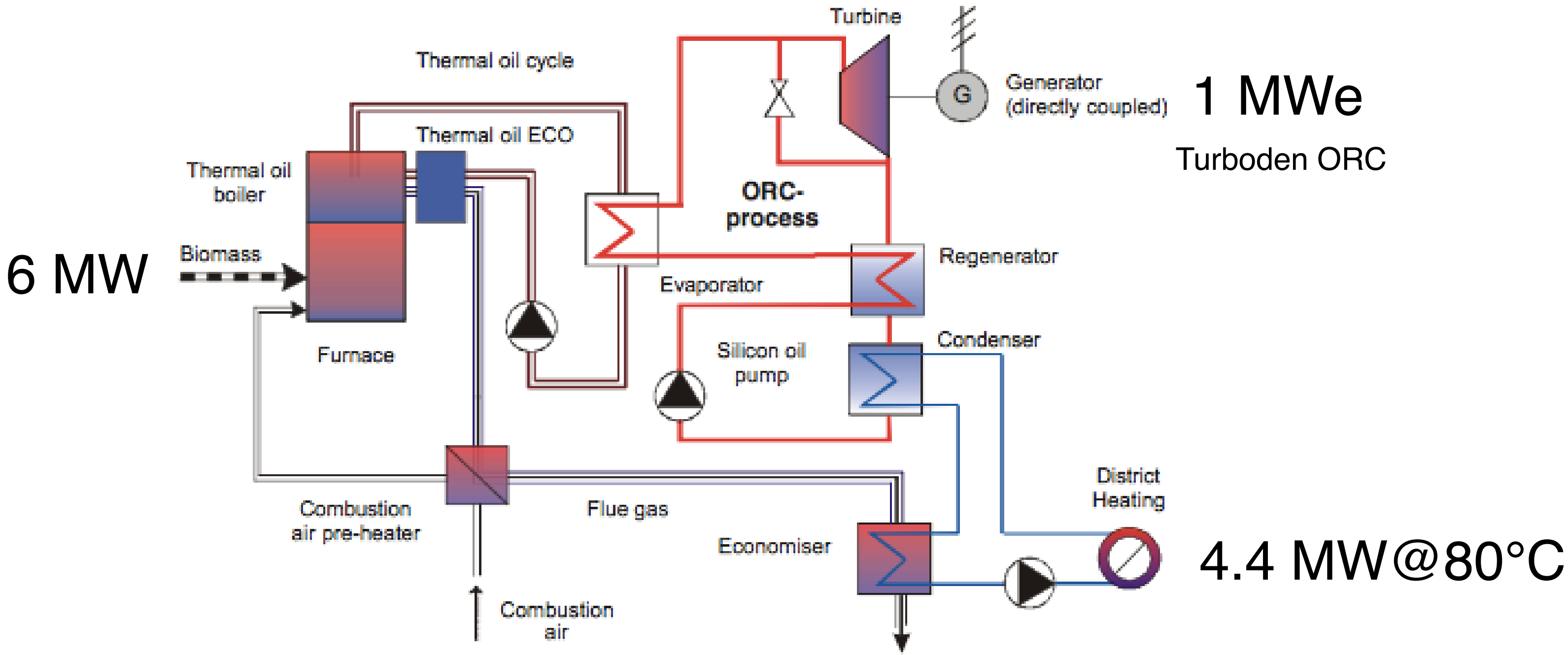
- **Conversion of heat into electricity**
  - T medium
  - Carnot eff : 50%
- **Applications**
  - Wood heating
  - Biogas engine
  - Geothermal energy

$$\dot{E} = \eta_{Carnot} \cdot \dot{m} \cdot LHV \cdot (1 - \frac{T_0}{\tilde{T}_{gases}})$$

$$\tilde{T}_{gases} = \frac{T^{add}_{gases} - T^{stack}_{gases}}{ln(T^{add}_{gases}) - ln(T^{stack}_{gases})}$$



ORC Cycle with biomass



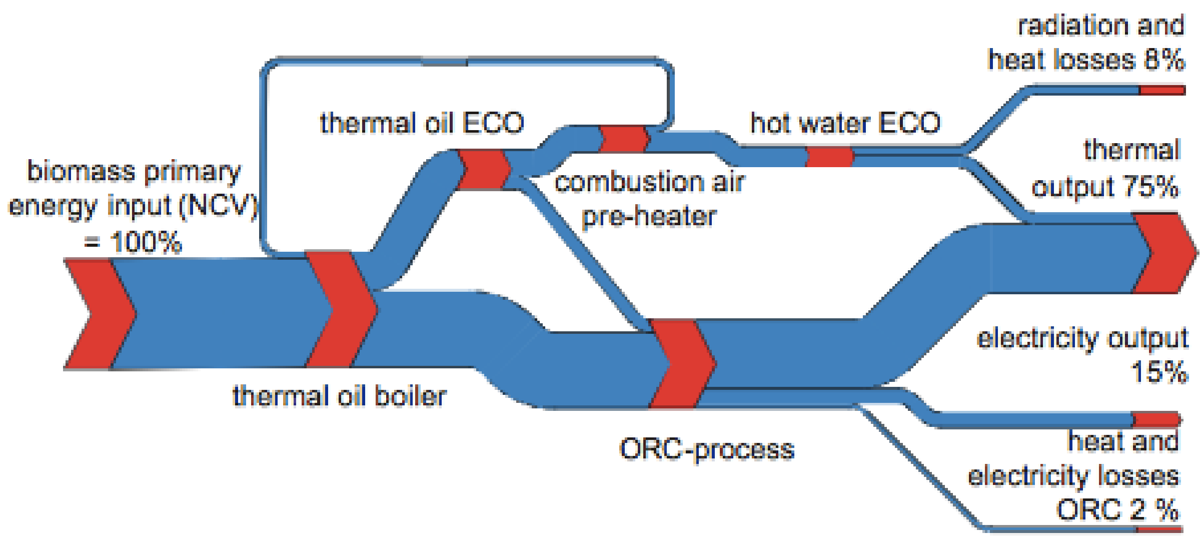


Figure 4. Energy balance of the biomass CHP plant in Lienz

International Nordic Bioenergy 2003 conference

Biomass to services

Rendements

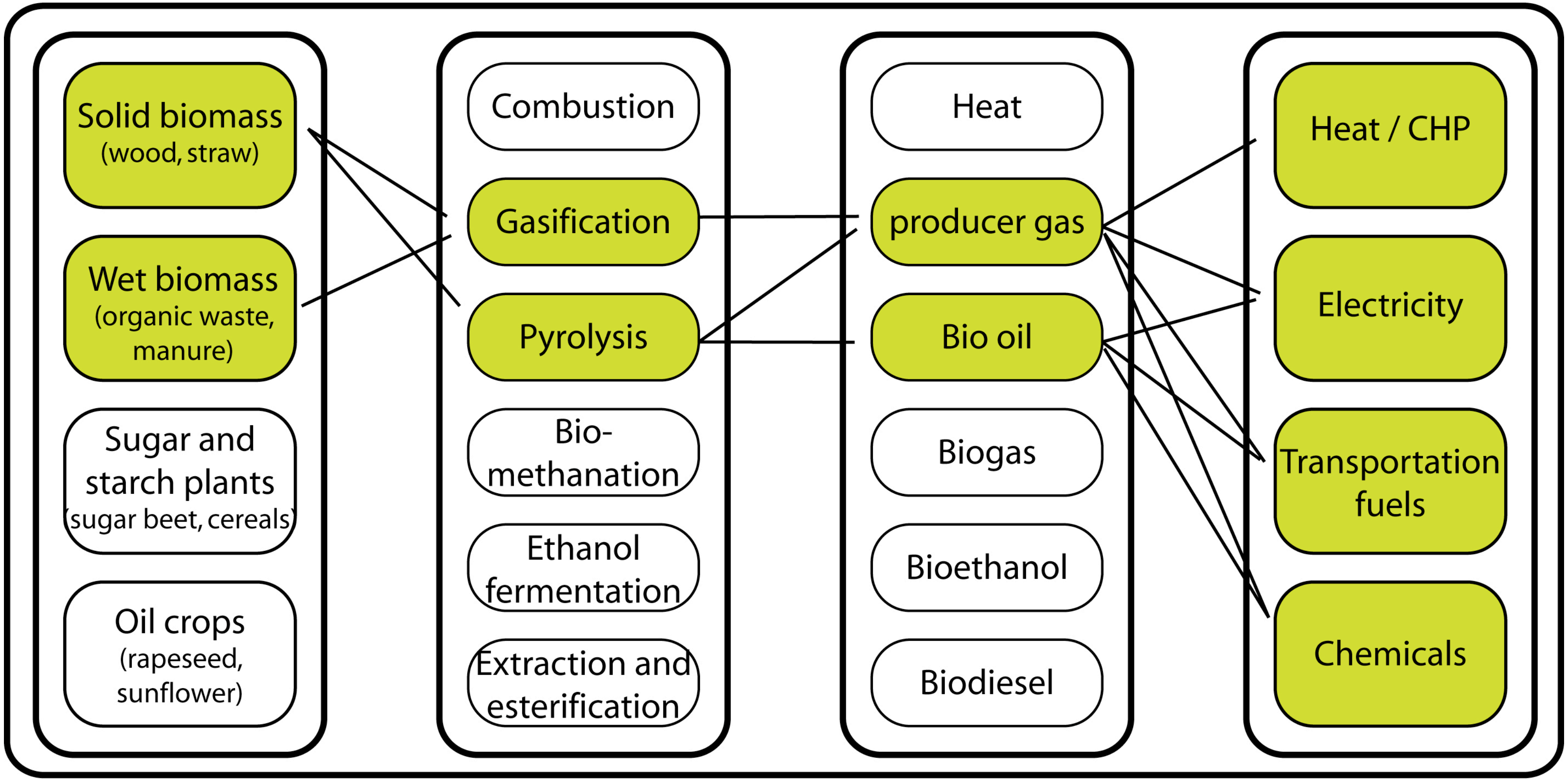
Technologie	Rendements [% du PCI] électrique	chaleur	Remarques/Source
Co-combustion			
Chaudière pellets	-1	80	maison individuelle (système complet)
	-1	90	Hoval AG
Chaudière copeaux	-1	90	chaleur à distance
Cycle vapeur	26	67	Projet Aubrugg, ZH
- turbine à condensation	20	30	petite échelle (Durena AG)
	28	40	grande échelle (Durena AG)
- turbine à contre-pression	15	70	petite échelle (Durena AG)
ORC	16	72	Turboden

Emissions compared to Natural gas

Nox x 2.5

Particulates x 25

Biomass conversion
Thermochemical routes



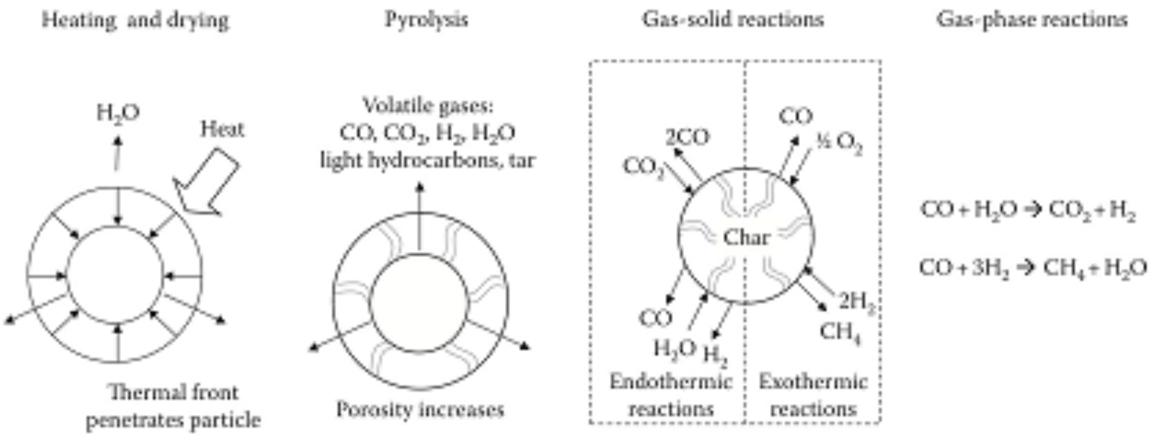
adapted from Chemical Engineering 10 (2006)

Gasification

$CH_{1.5}O_{0.67}$ + H_2O-> CO+1.08H_2 (ΔH=101 kJ/mol (700-900°C, 1 atm))

wood steam syngas

(gasifying agent)

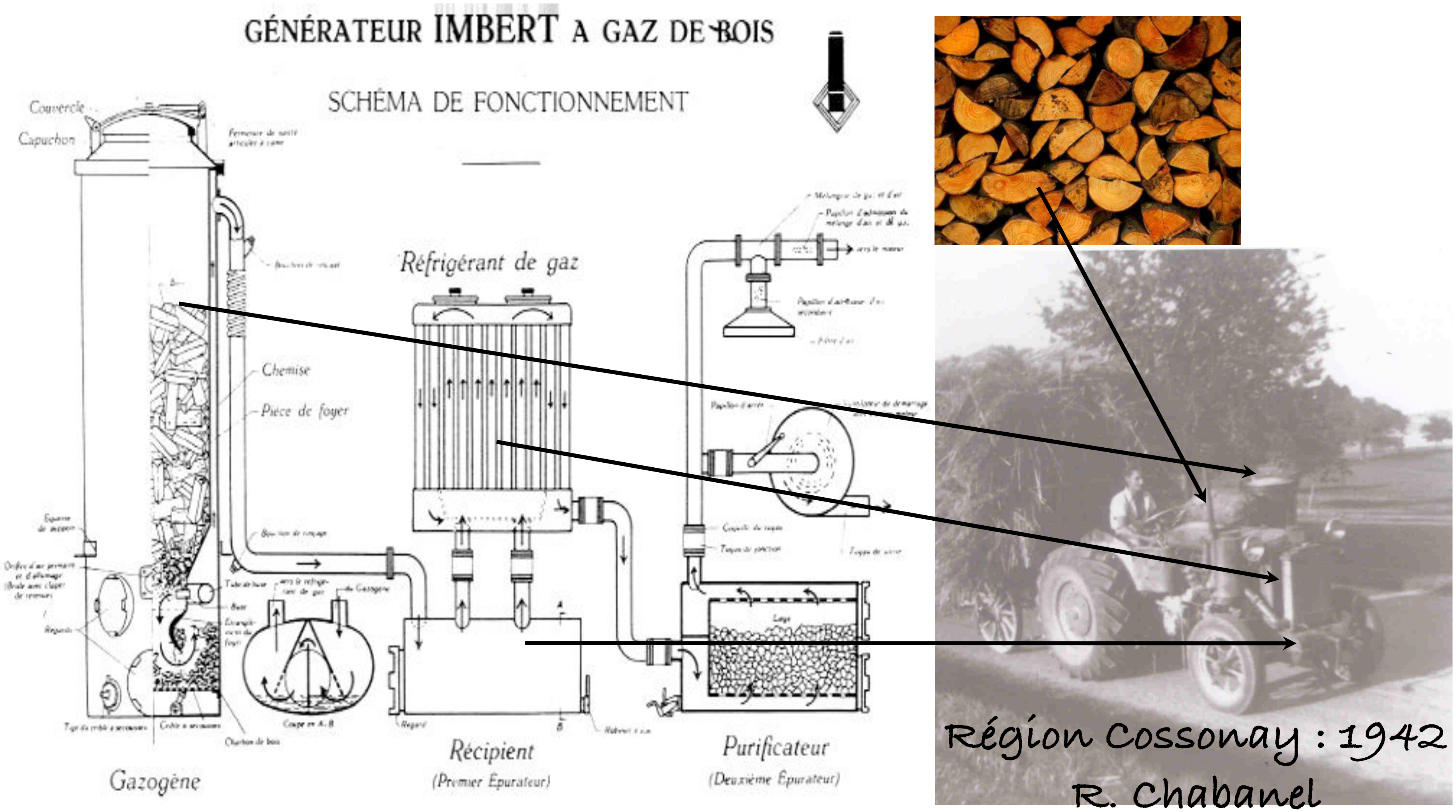


✓**Able to convert lignocellulosic biomass**
✓**Various final products, including drop in fuels**

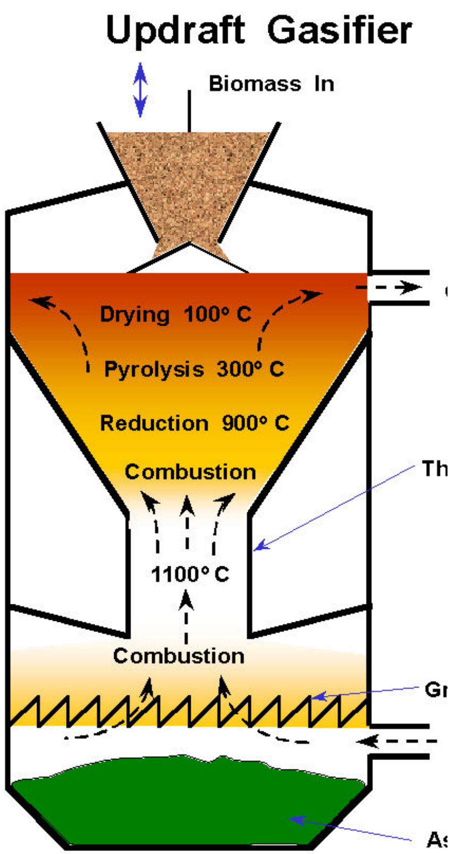
☒**Remaining R&D issues**
☒**Suitable only for medium to large scale applications**

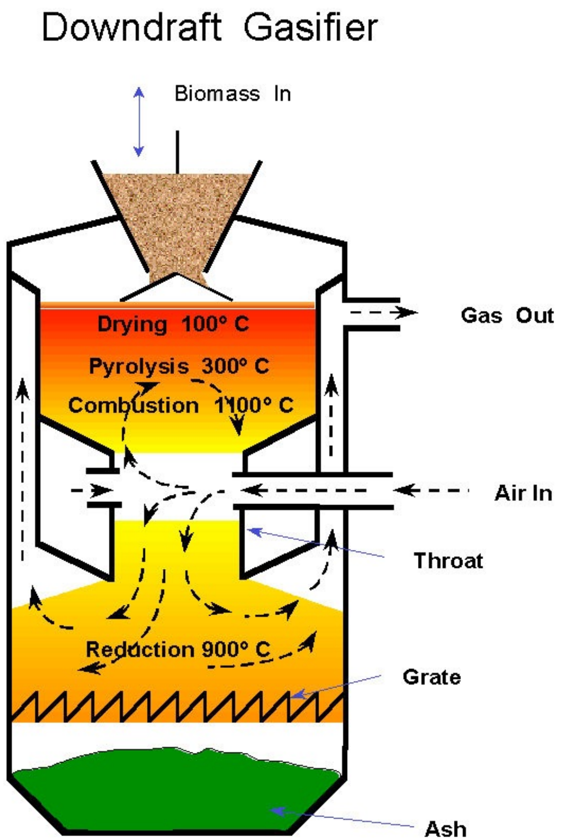
References: MIT open courseware:William H. Green Sustainable Energy November 16, 2010
Capucine Dupont, LTB CEA Grenoble
www.springvale.biz/course%20notes/week11%20Biomass%20wood%20combustion1/week11.htm

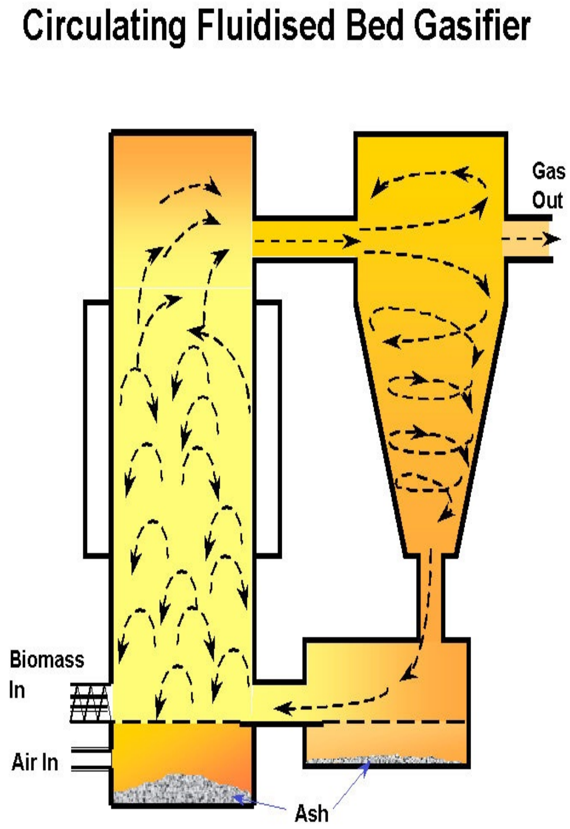
Gasification & Fuel



Different gasifiers







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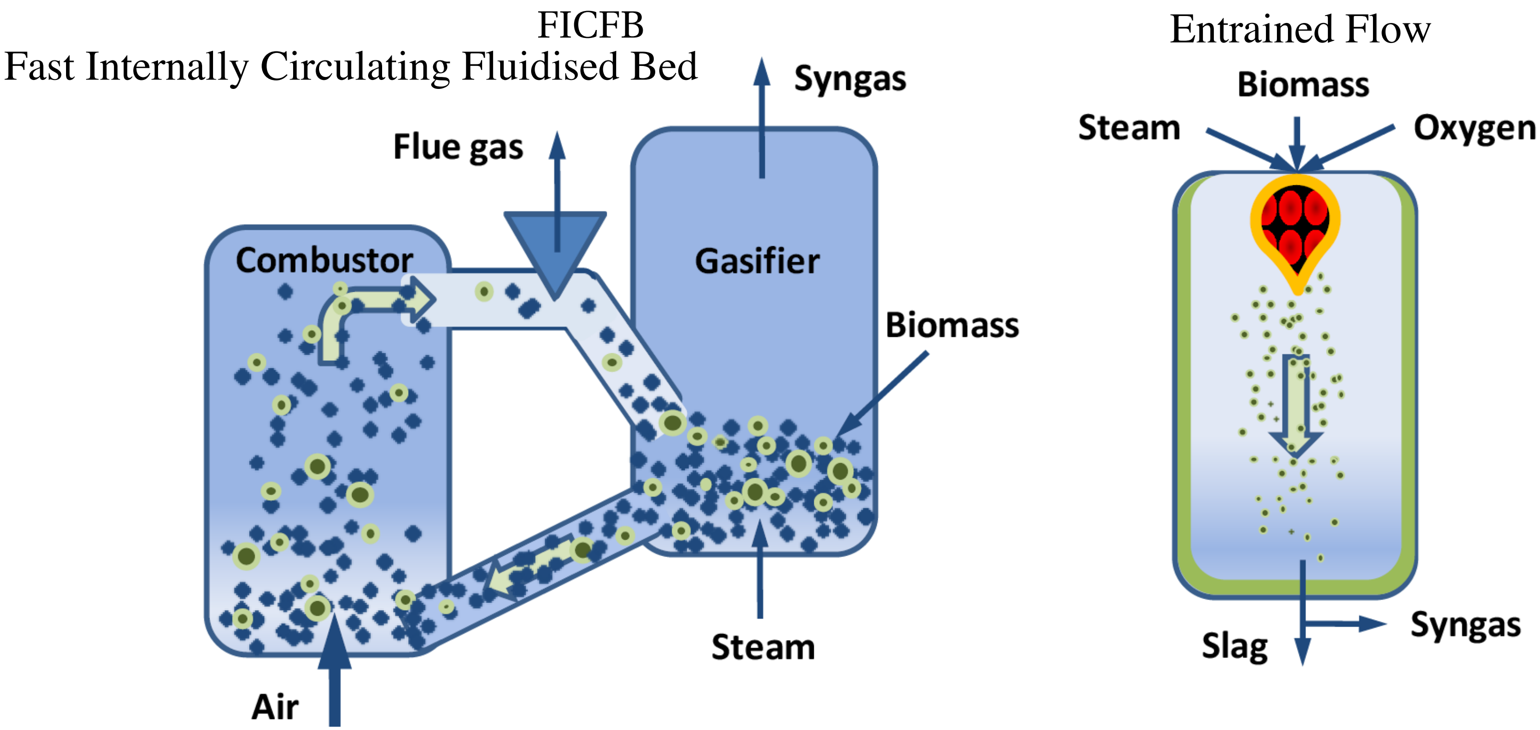
www.springvale.biz/course%20notes/week11%20Biomass%20wood%20combustion1/week11.htm

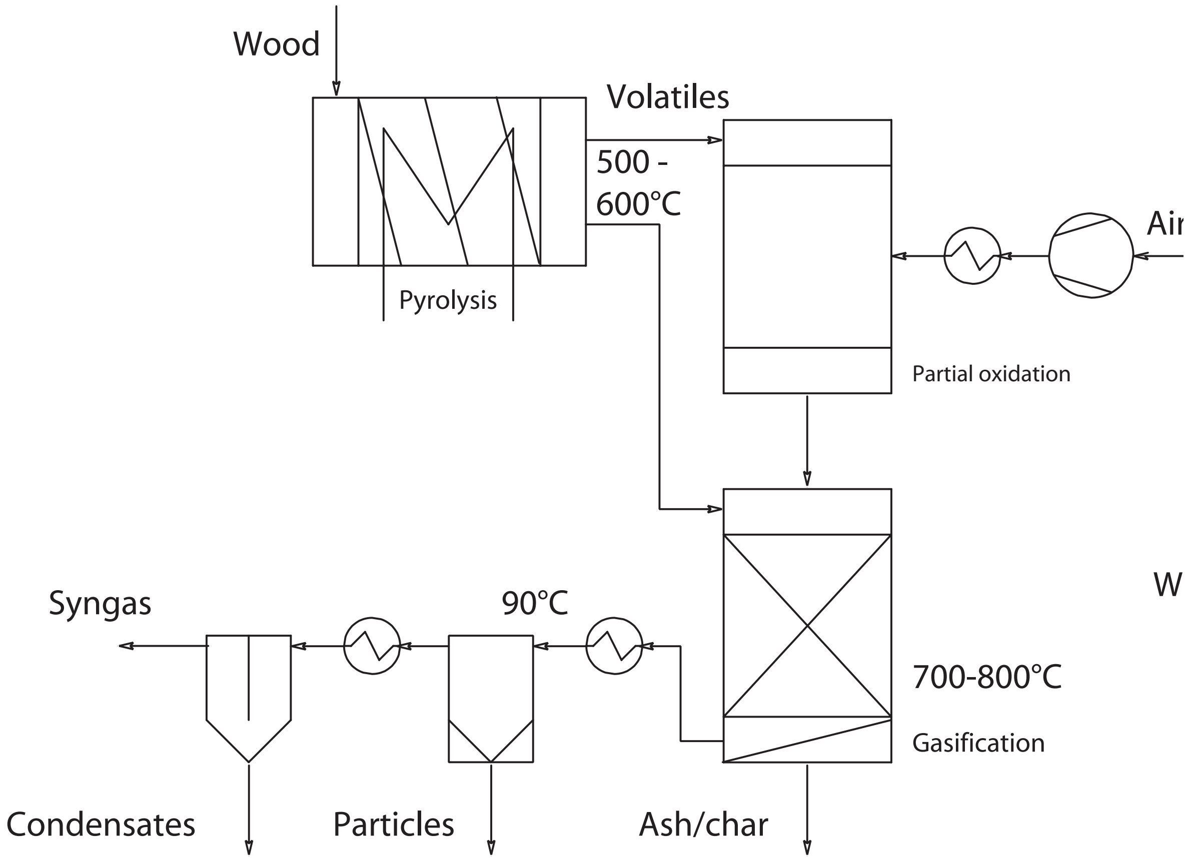
Types of gasifiers
Comparing operating conditions



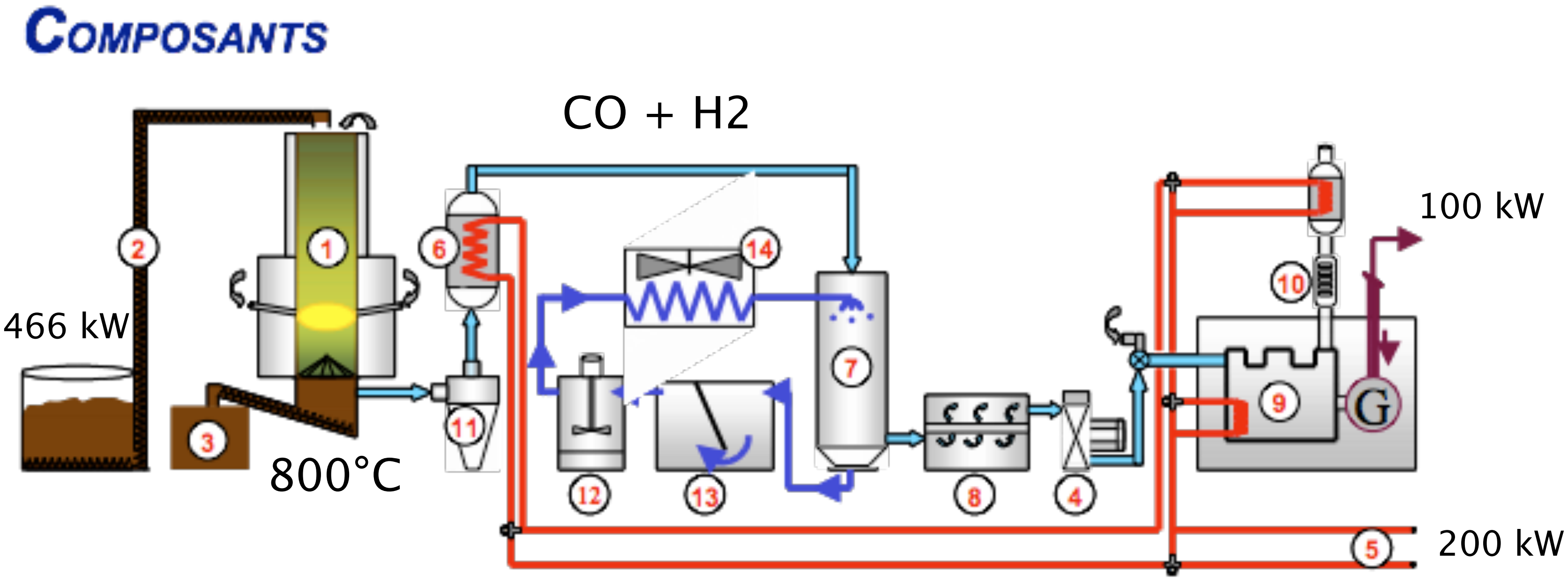
Temperature	800-1000 °C	1200-1500 °C
Pressure	1-4 bar	30-80 bar
Gas residence time	10 s	seconds
Solid residence time	several minutes	seconds
Particle size	50-150 mm[a]	< 0.1 mm
Gasification agent	steam	steam/O_2

E. Peduzzi : PhD Thesis EPFL, 2015

Viking gasifiers



Cogeneration : Gasification



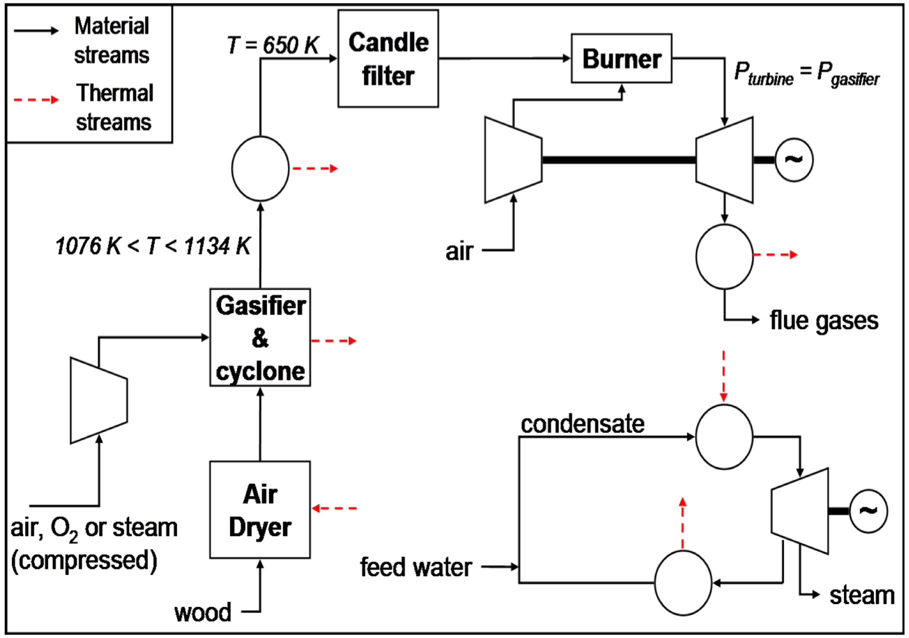
Légende :		
1. Réacteur	6. Echangeur de chaleur	11. Cyclone
2. Chargement du bois	7. Colonnes de lavages	12. Cuve de floculation
3. Evacuation des cendres	8. Filtrations	13. Décanteur
4. Ventilateur	9. Moteur à gaz et génératrice	14 . Aéro-refroidisseur
5. Circuit de chauffage	10. Catalyseur	

MENAG MANAGEMENT SA
XYLOWATT SA
Direction: G. Lagier
En Budron A12
1052 Le Mont-sur-Lausanne

Tél. +41 (0)21 651 69 69

Energy flow diagrams of optimisation scenarios

Hot gas cleaning and gas turbine



Hot Gas Cleaning (pros and cons)

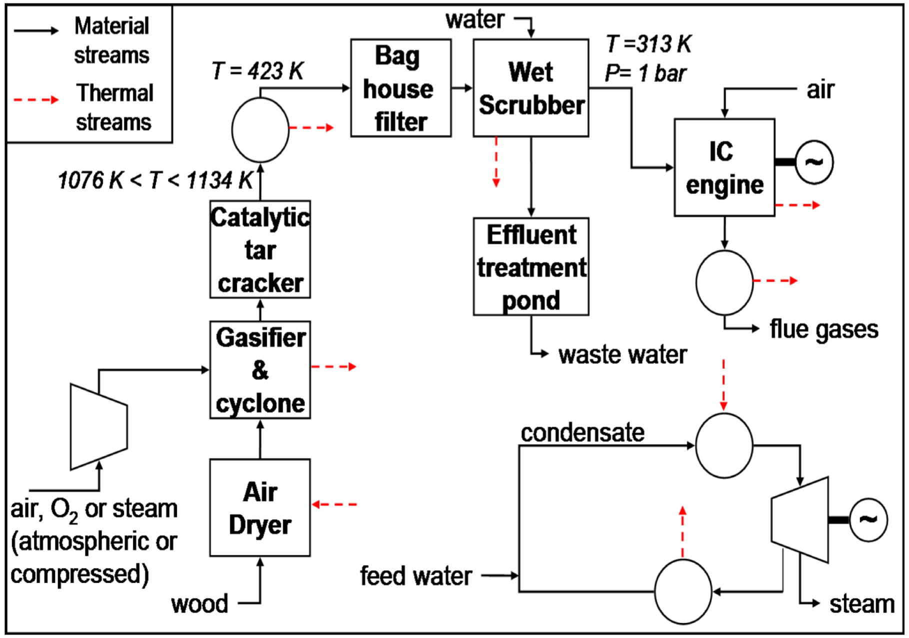
\+ no tar condensation (→ only particulates)

\- 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

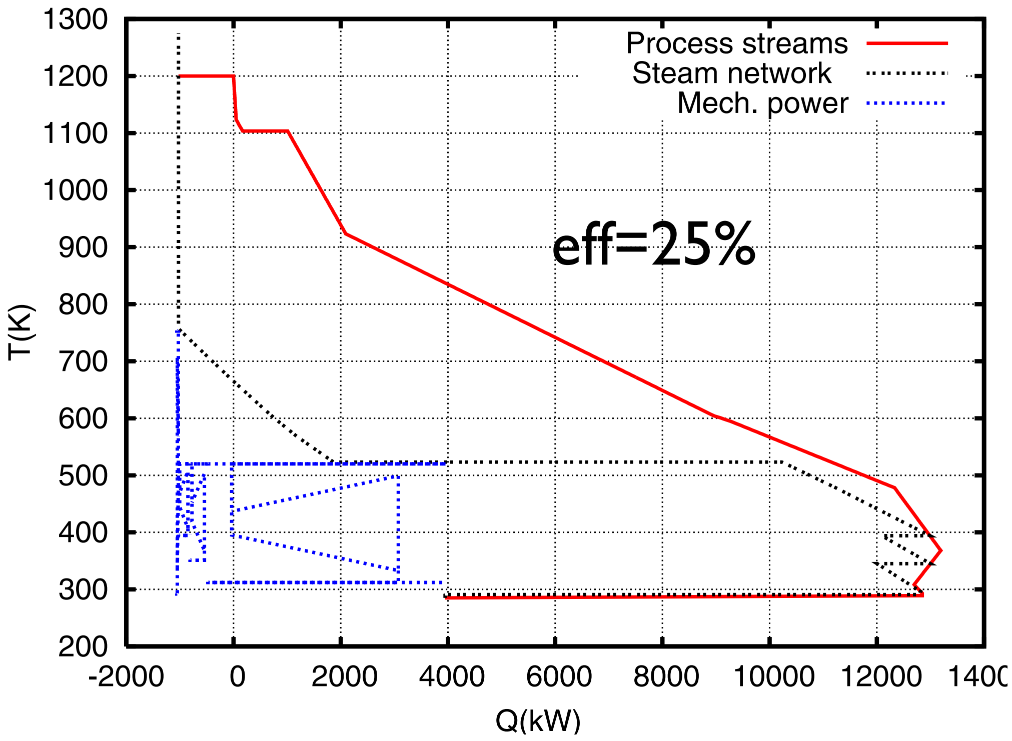
\+ possible to export, or to further process syngas –e.g. SNG)

\+ also feasible with gas turbine

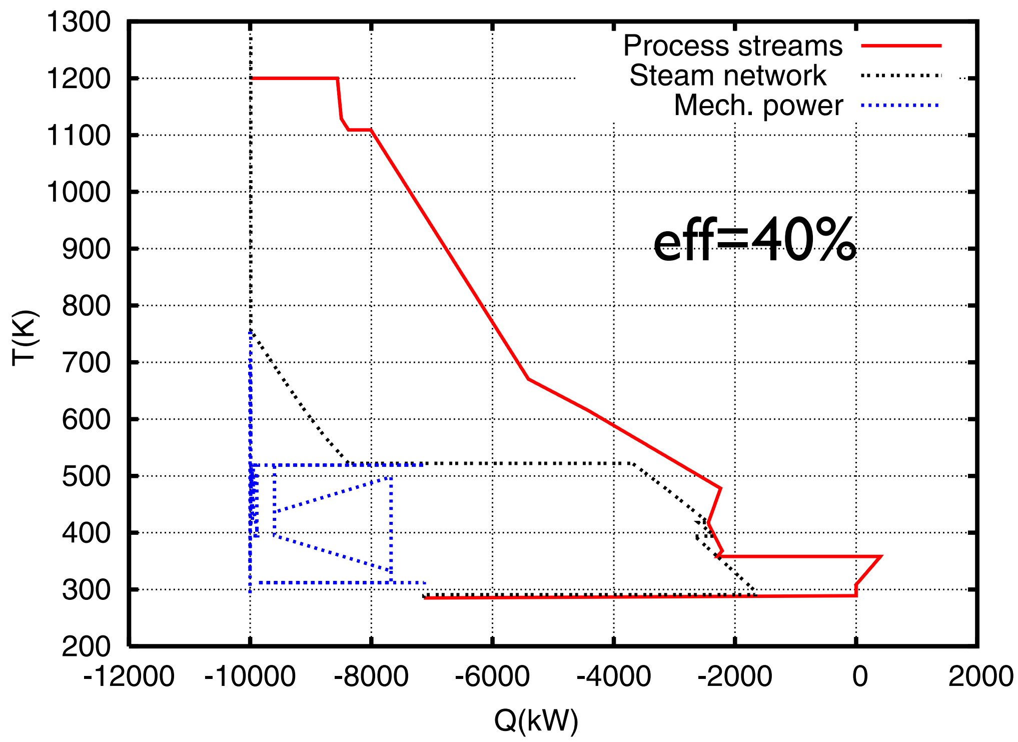
\+ Relatively mature cleaning technologies

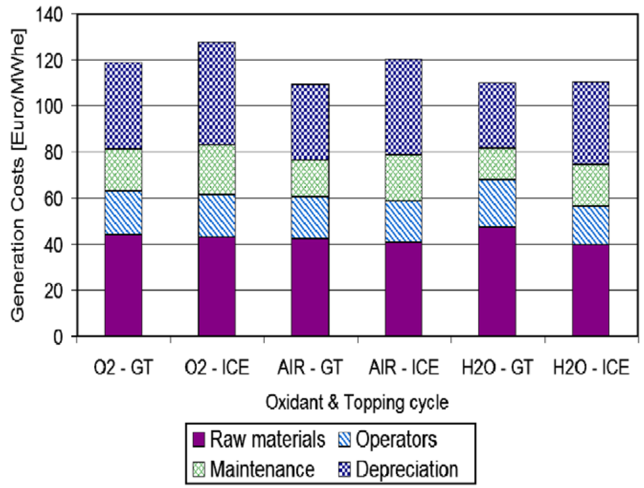
Reactor (n. iterations)		O_2 gasification (15000)		Air gasification (15000)		H_2O gasification (15000)	
	Units	Max eff.	Min cost	Max eff.	Min cost	Max eff.	Min cost
Invest. Costs	k€	29717	19129	32939	17122	26335	14339
Exergy eff.	-	0.32	0.13	0.33	0.10	0.34	0.19
Electric eff.	-	0.41	0.17	0.43	0.13	0.43	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

Gas turbine integration



Gas engine integration





Biomass to services

Rendements

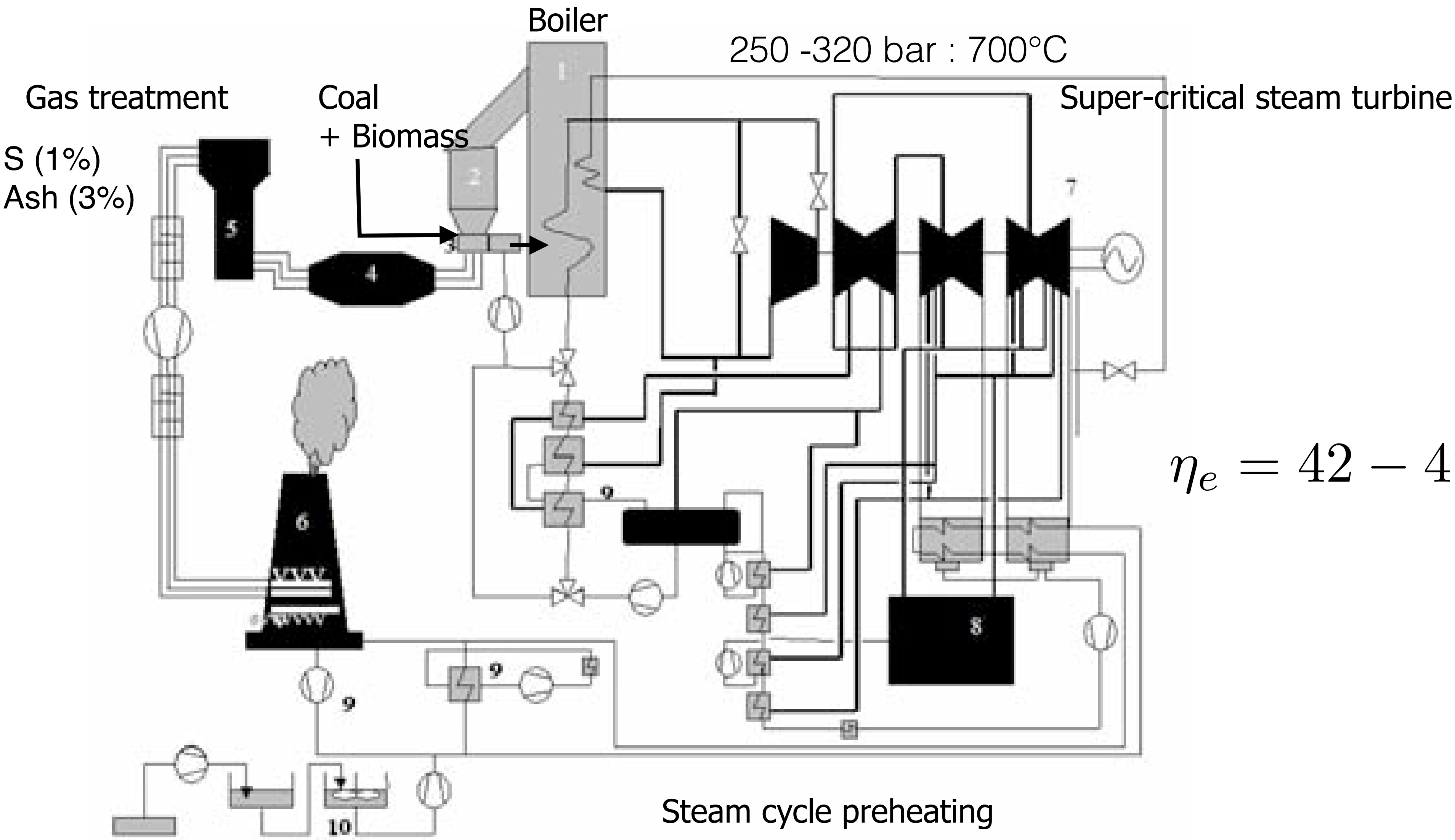
Technologie	Rendements [% du PCI] électrique	chaleur	Remarques/Source
Co-combustion			
Chaudière pellets	-1	80	maison individuelle (système complet)
	-1	90	Hoval AG
Chaudière copeaux	-1	90	chaleur à distance
Cycle vapeur	26	67	Projet Aubrugg, ZH
- turbine à condensation	20	30	petite échelle (Durena AG)
	28	40	grande échelle (Durena AG)
- turbine à contre-pression	15	70	petite échelle (Durena AG)
ORC	16	72	Turboden
Gazéification			
& moteur	25	55	Güssing
& moteur, ORC	34	36	pilote Repotec
& cycle combiné	32	51	demo, Stahl (1999)
& cycle combiné	43	0	potentiel, Brown et al. (2009)

Emissions compared to Natural gas

Nox x 2.5

Particulates x 25

Co-Combustion in Coal power plants



$$\eta_e = 42 - 47\%$$

Examples of supercritical plants

Table 3.4 Thermodynamic main parameters of supercritical plants in Denmark

Designation	Unit	Studstrup Unit 3 & 4	Fynsværket Unit 7	Esbjerg Unit 3	Amager Unit 3	Avedøre Unit 1
Net output	MW	350	390	377	250	250
Main steam pressure	Bar	250	250	250	245	245
Main steam temperature	°C	540	540	560	545	545
Reheat temperature	°C	540	540	560	545	545
Feedwater temperature	°C	260	280	275	275	275
Condenser pressure	mbar	27	27	23	37	37
Stack temperature	°C	125	122	105	110	110
Net efficiency	%	42	43.5	45	42	42
Commissioning year	-	1984/85	1991	1992	1989	1990

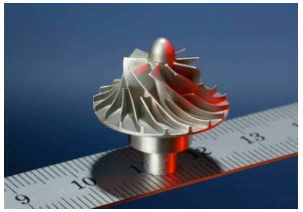
Système hybride pile à combustible

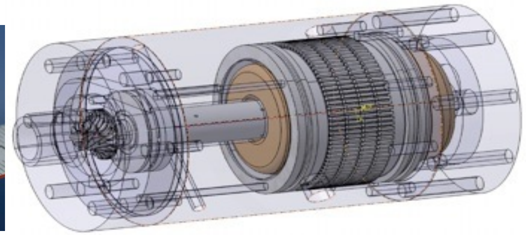
$$\eta_d = \frac{E^-}{CH4^+_{LHV}} = 80\%$$

Fuel cell

15 kWe

Gas turbine





6 kWe

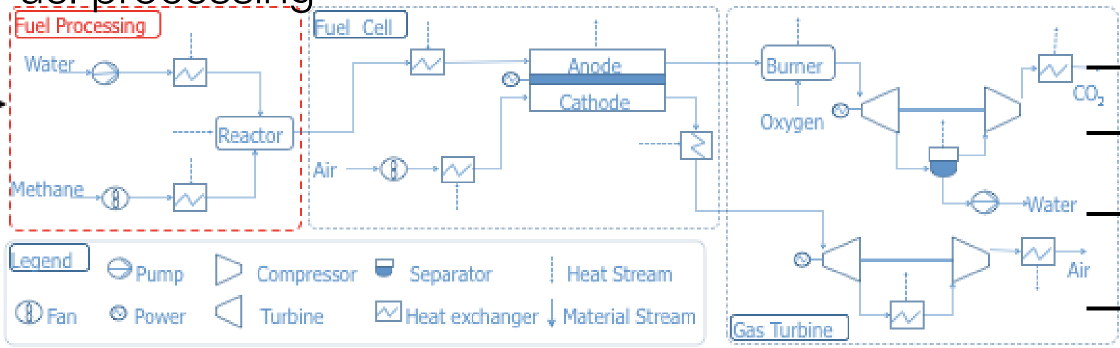
Fuel processing

26.3 kW_{LHV}

CH4

Bio CH4

100%



CO_2 to recycling ?

Elec 80 - 82% 21 kWe

Heat 18- 16% 5.3 kWth

H_2O

Facchinetti, M, Daniel Favrat, and Francois Marechal. "Sub-atmospheric Hybrid Cycle SOFC-Gas Turbine with CO2 Separation." *PCT/IB2010/052558, 2011*.

Process integration

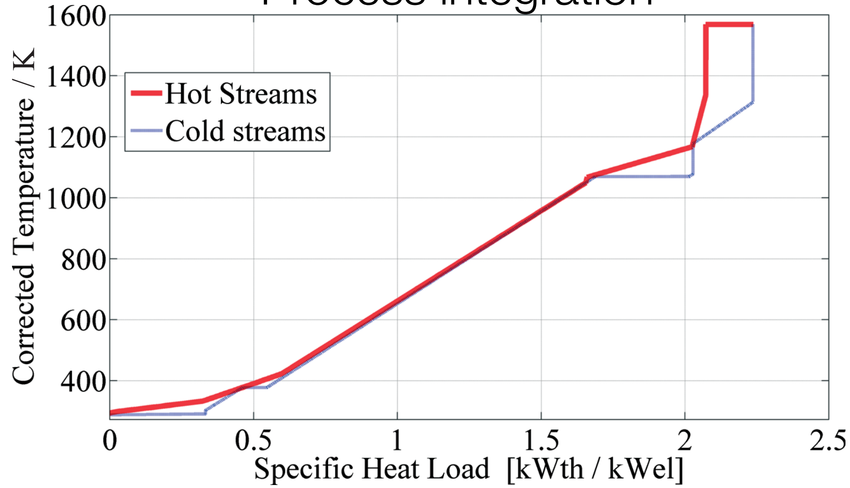
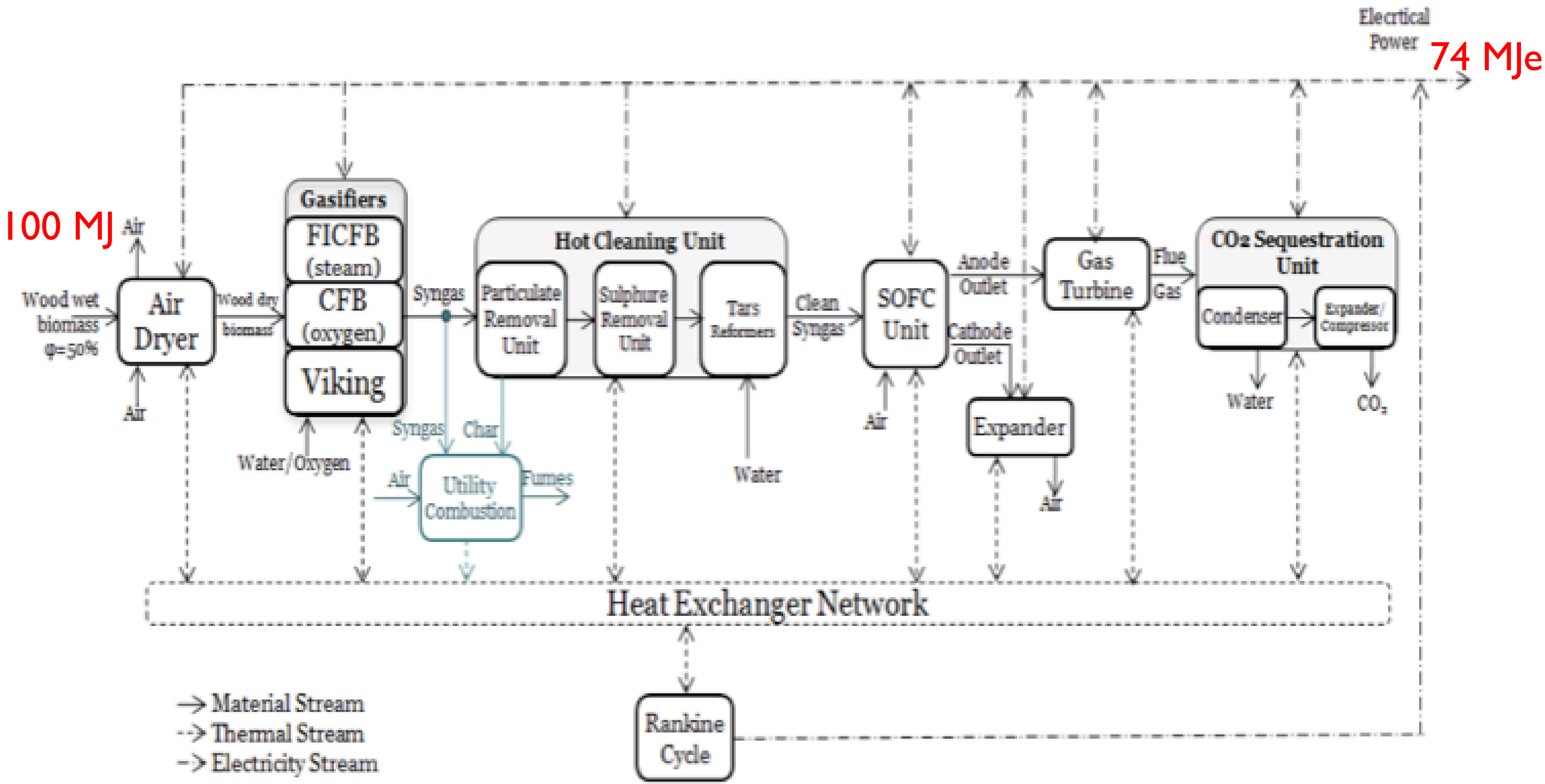


Fig. 7 HCox composite curves of optimal solution with $\pi = 3$ and max TIT = 1,573 K.

2.2 kWth/kWel

Facchinetti, Emanuele, Daniel Favrat, and François Marechal. *Fuel Cells*, no. 0 (2011): 1-8.

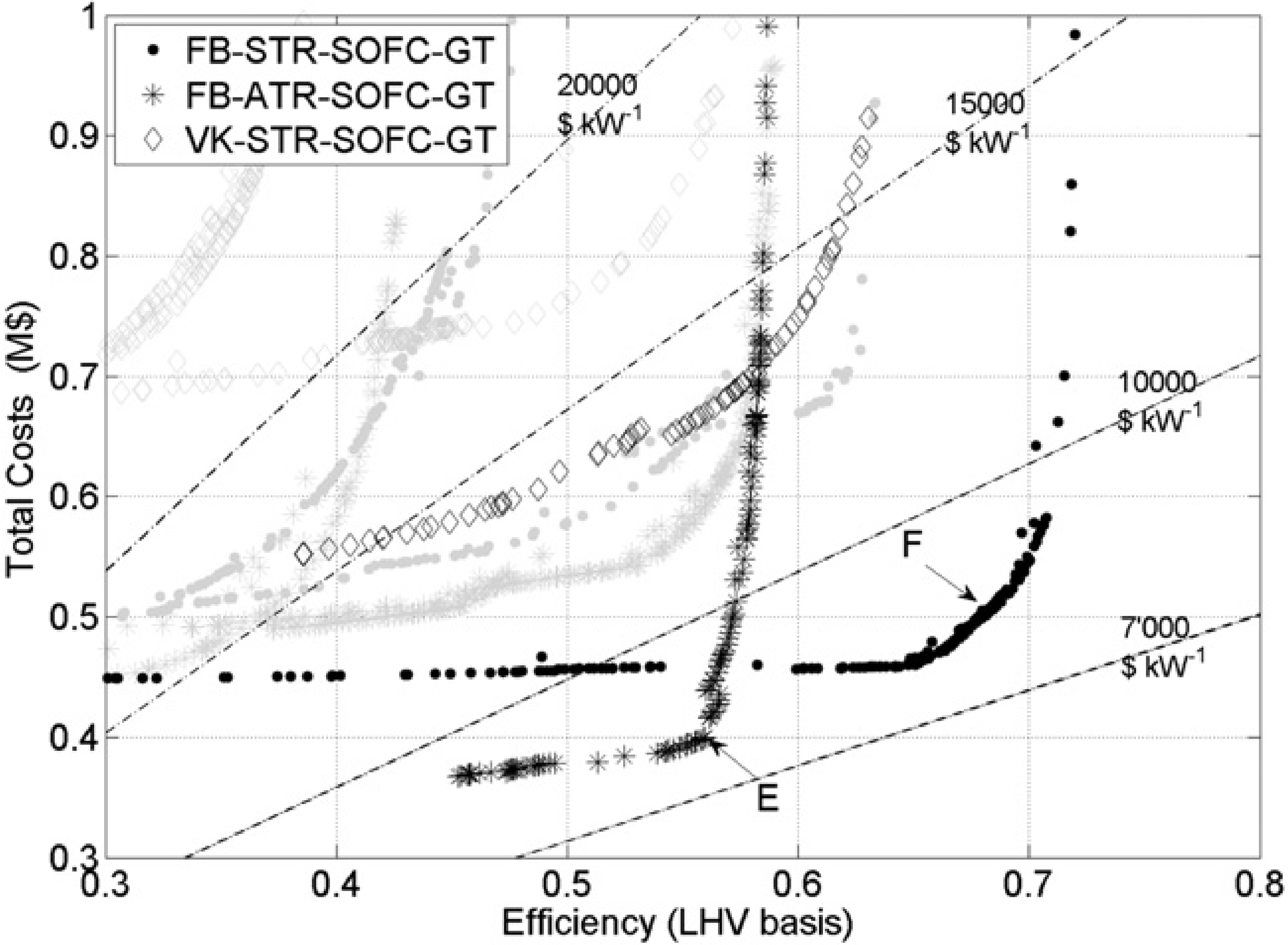


Elecrtical
Power
74 MJe
100 MJ
Air
Wood wet
biomass
φ=50%
Air
Dryer
Air
Wood dry
biomass
Gasifiers
FICFB
(steam)
CFB
(oxygen)
Viking
Water/Oxygen
Syngas
Syngas
Char
Air
Utility
Combustion
Fumes
Hot Cleaning Unit
Particulate
Removal
Unit
Sulphure
Removal
Unit
Tars
Reformers
Water
Clean
Syngas
SOFC
Unit
Air
Anode
Outlet
Cathode
Outlet
Expander
Air
Gas
Turbine
Flue
Gas
CO2 Sequestration
Unit
Condenser
Expander/
Compressor
Water
CO_2
Heat Exchanger Network
Rankine
Cycle
Material Stream
Thermal Stream
Electricity Stream

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

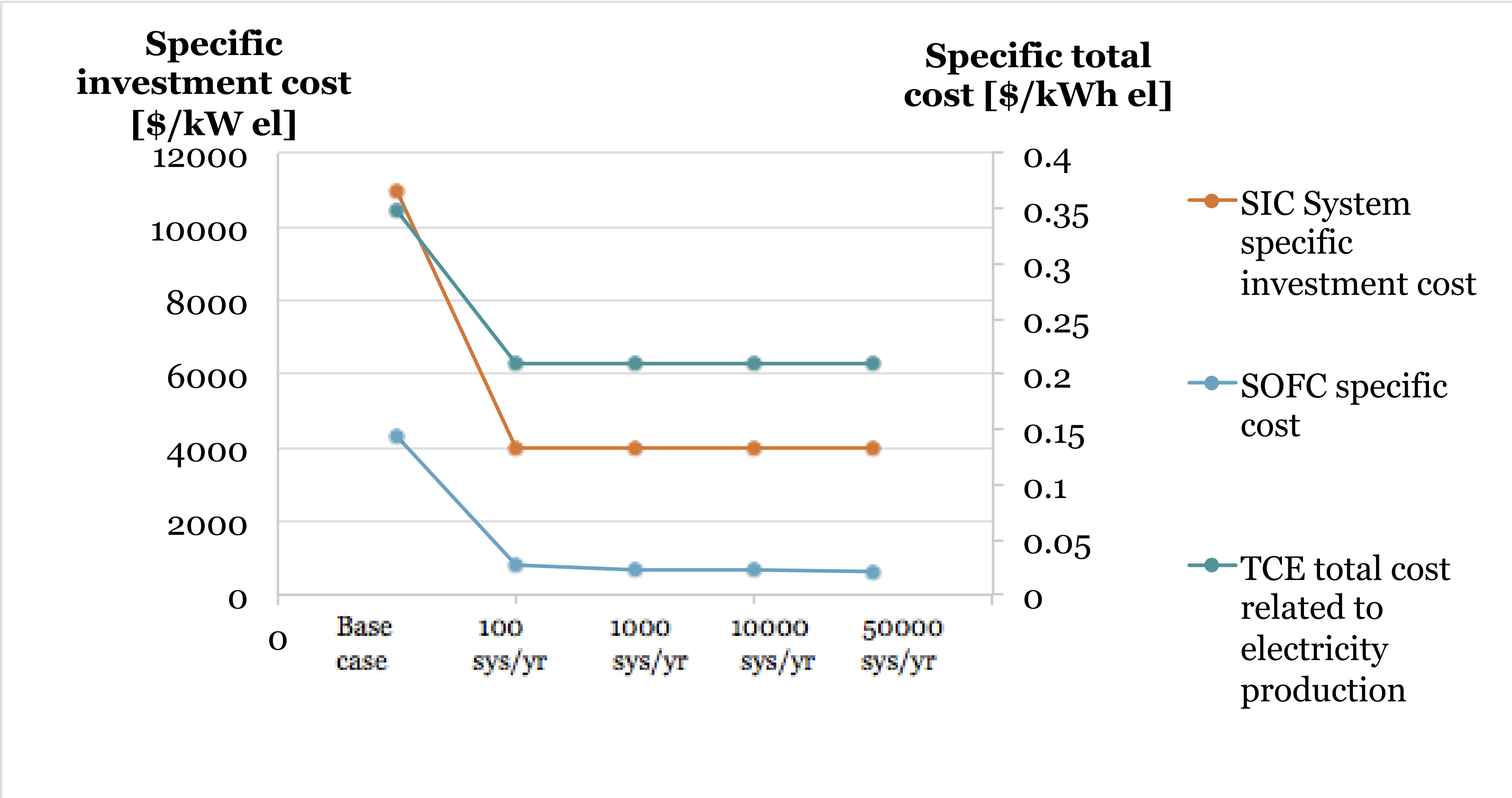
SOFC-Gasifiers

		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

Reduction of the technology cost

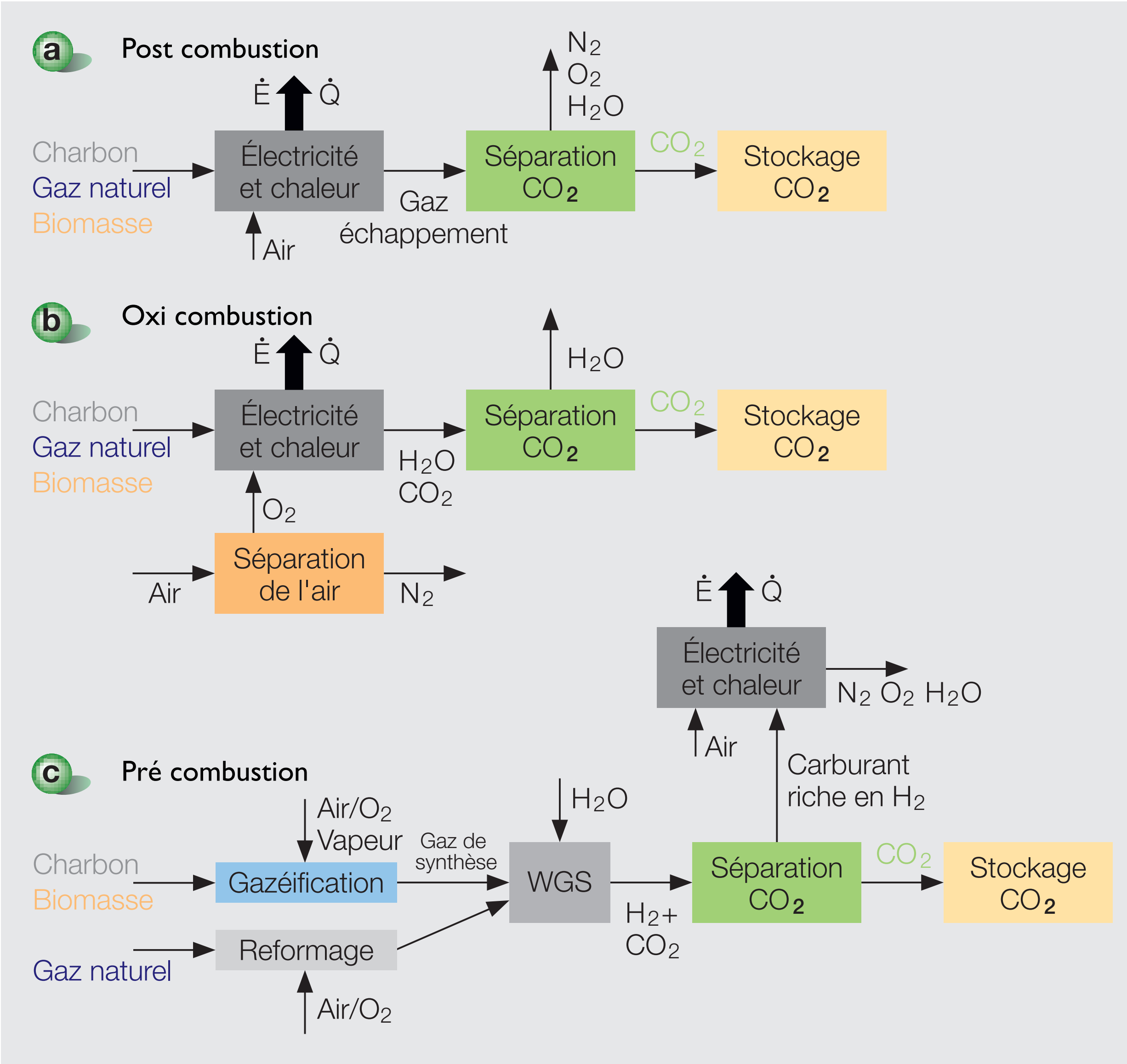
- SOFC element = 78 % of the total cost

Reducing the system cost as a function of the number of units.



Caliandro P, Tock L, Ensinas A, Marechal F. Thermo-economic optimization of a Solid Oxide Fuel Cell-Gas Turbine system fuelled with gasified lignocellulosic biomass. Proceedings of ECOS 2013, Guilin, China, July 16-19, 2013.

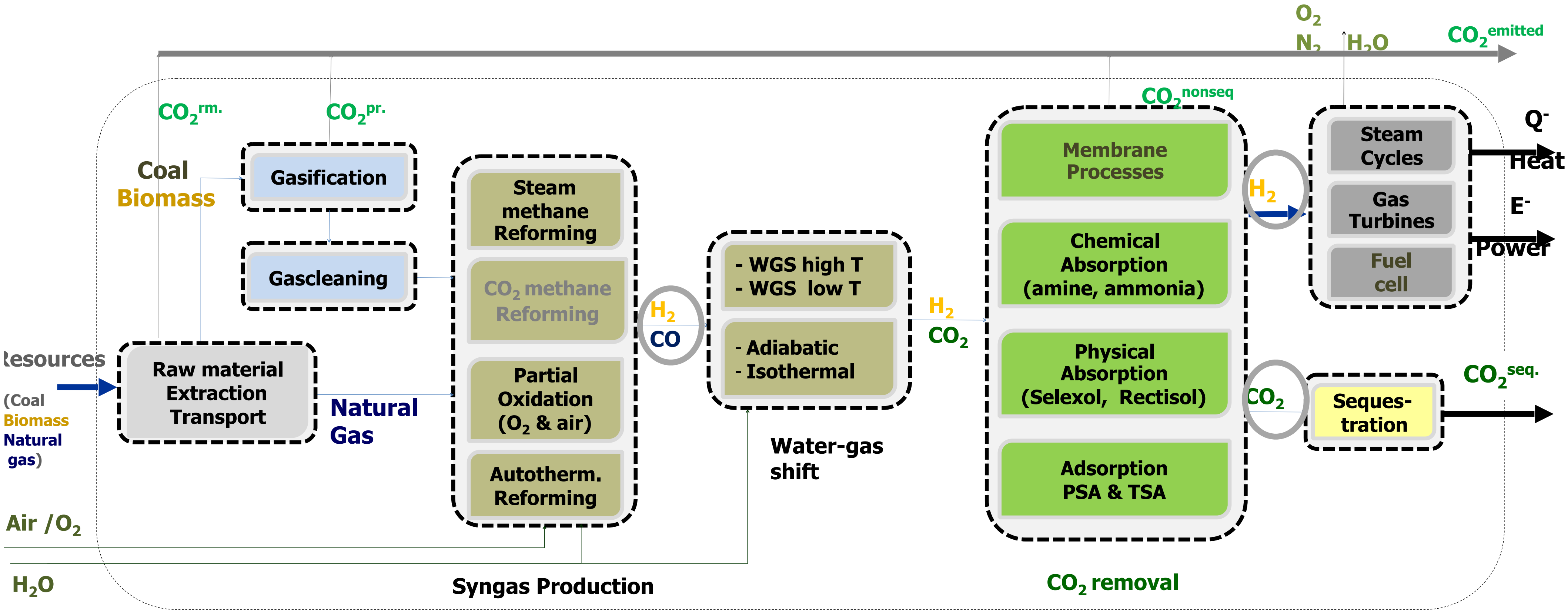
CO2 Capture



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

Physical model

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



$$\text{SMR}: CH_4 + H_2O \xleftrightarrow{\Delta\tilde{h}_r^o = 206 kJ/mol} CO + 3H_2$$

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

$$\text{POX}: CH_4 + \tfrac{1}{2}O_2 \xleftrightarrow{\Delta\tilde{h}_r^o = -36 kJ/mol} CO + 2H_2$$

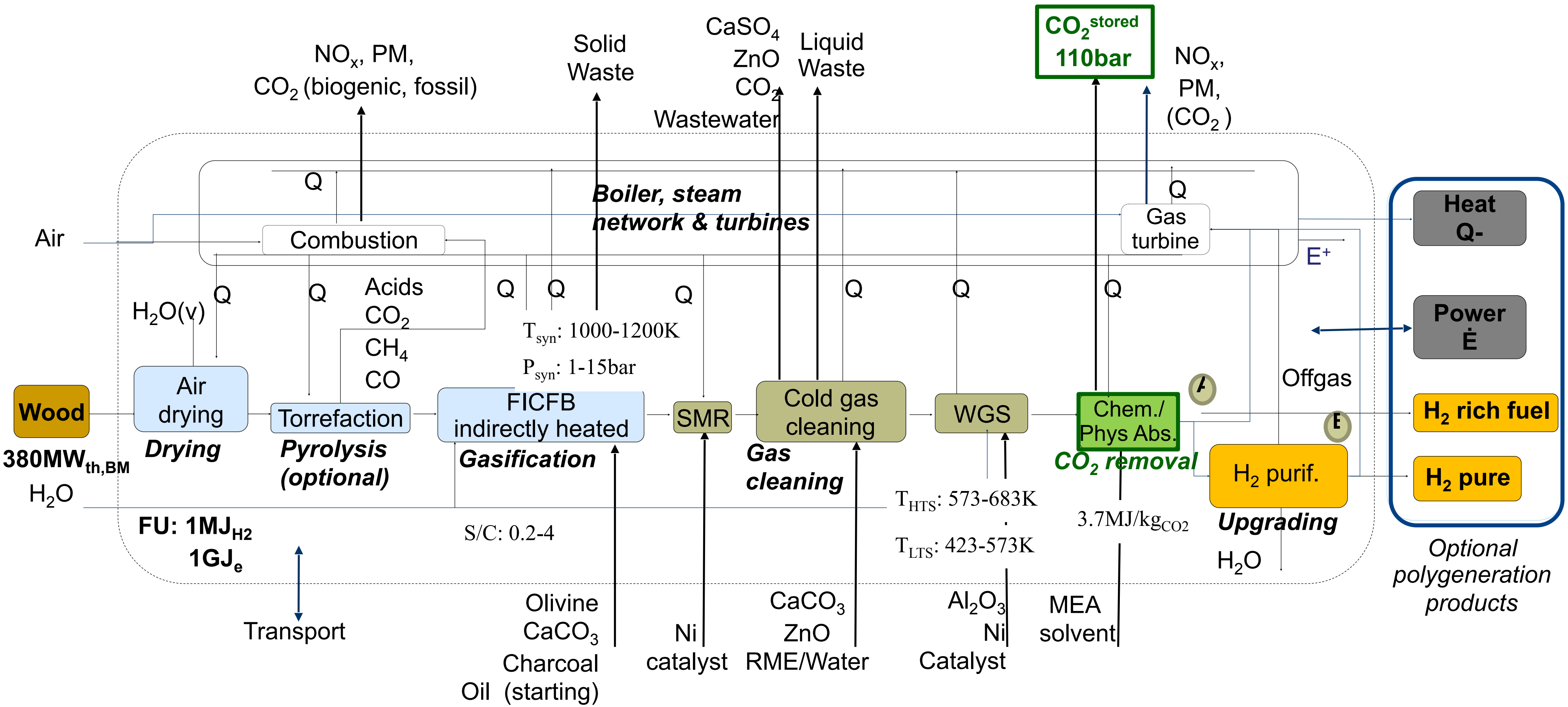
Process units ?

Process configuration ?

Decision variables ?

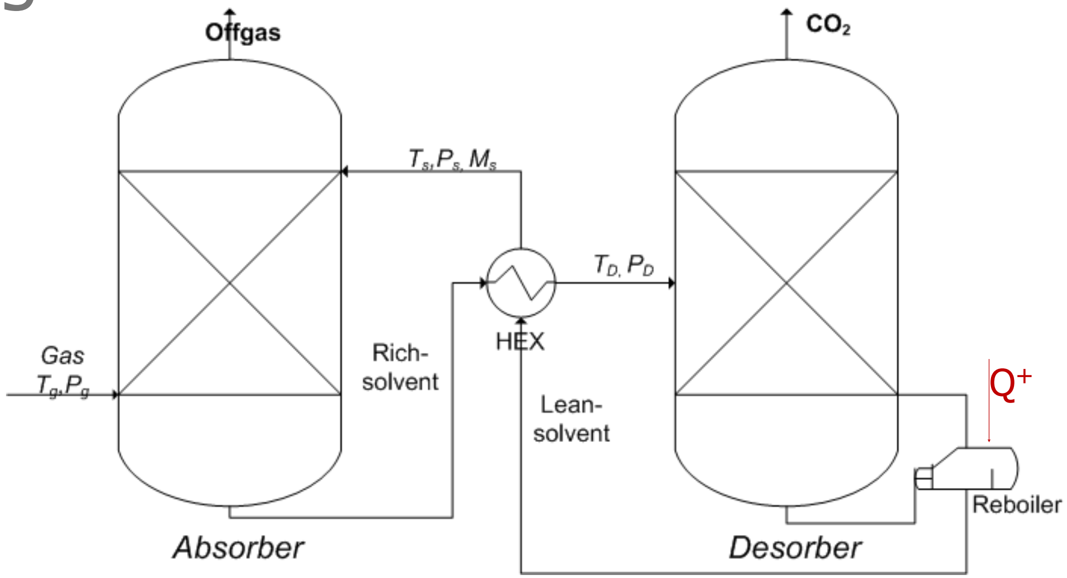
[6] Tock et al. IJHE 2012

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

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

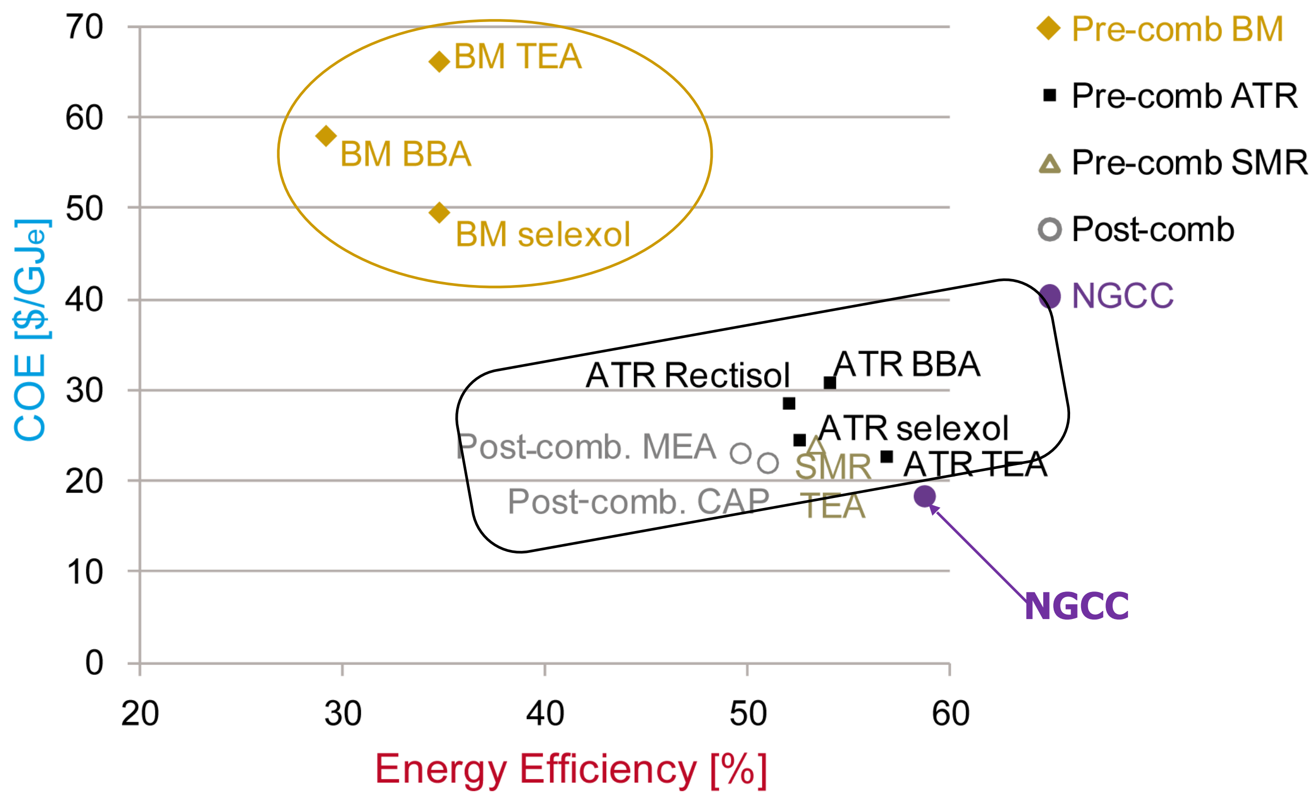


Operating conditions ? **Separation/purification capacity ?** **Energy requirement ?** **Costs ?**

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

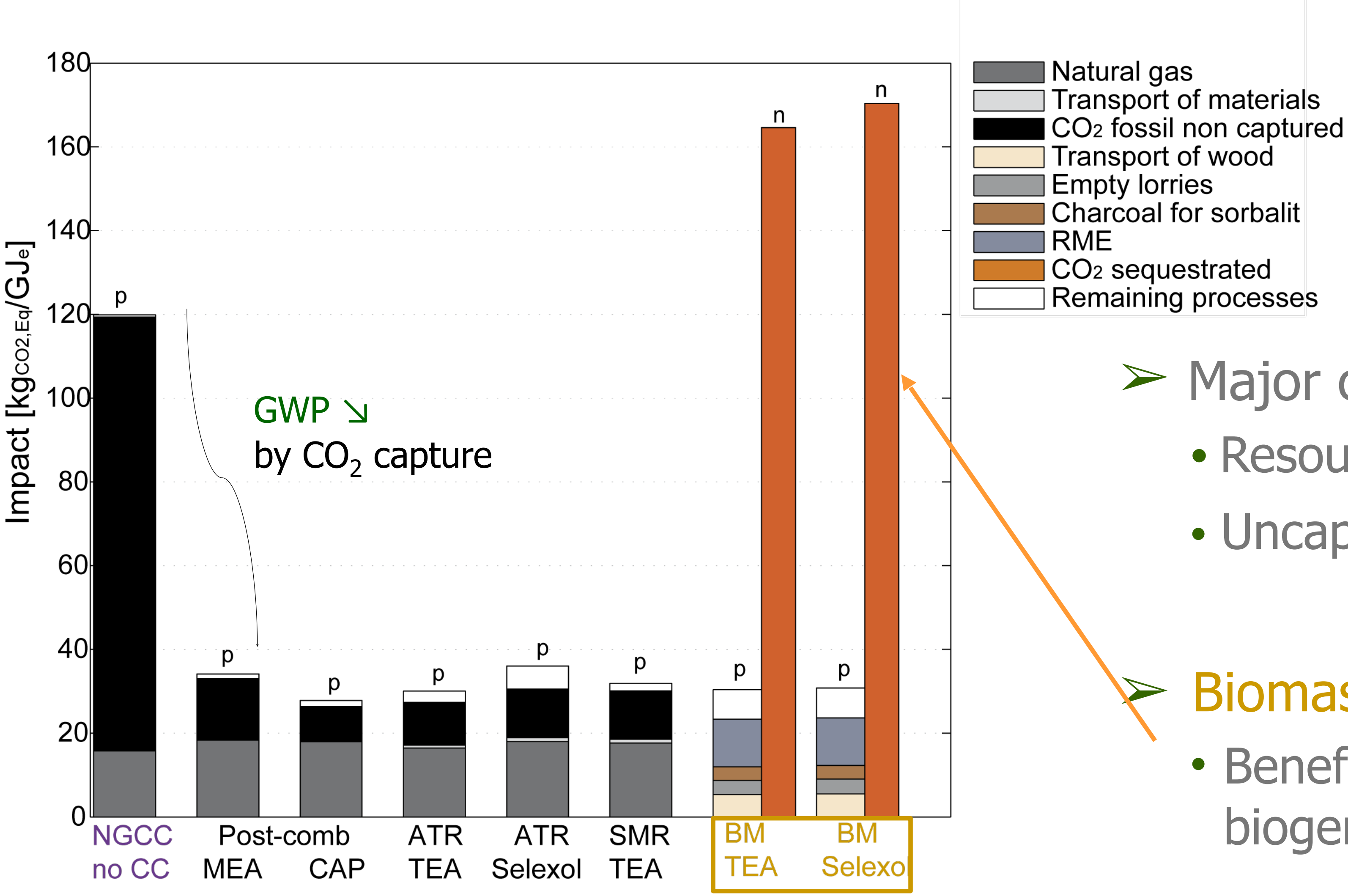


  - Competition between post- and pre-combustion

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

◆ CO_2 capture environmental performance

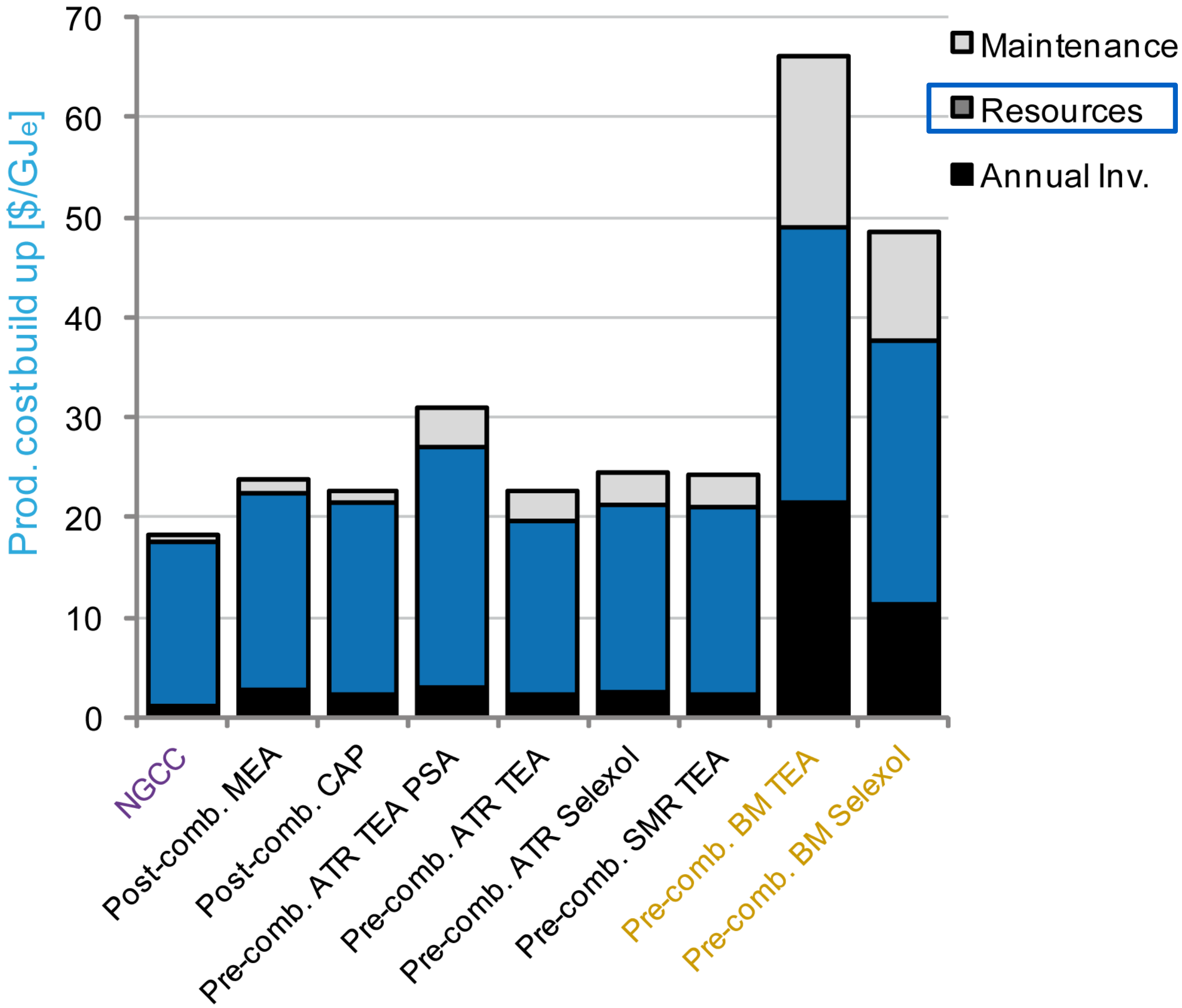
- IPCC 07: Global warming potential (FU=1GJe)



➢ Major contributions
- Resource extraction
- Uncaptured CO_2

➢ Biomass fed process
- Benefit of capturing biogenic CO_2 !

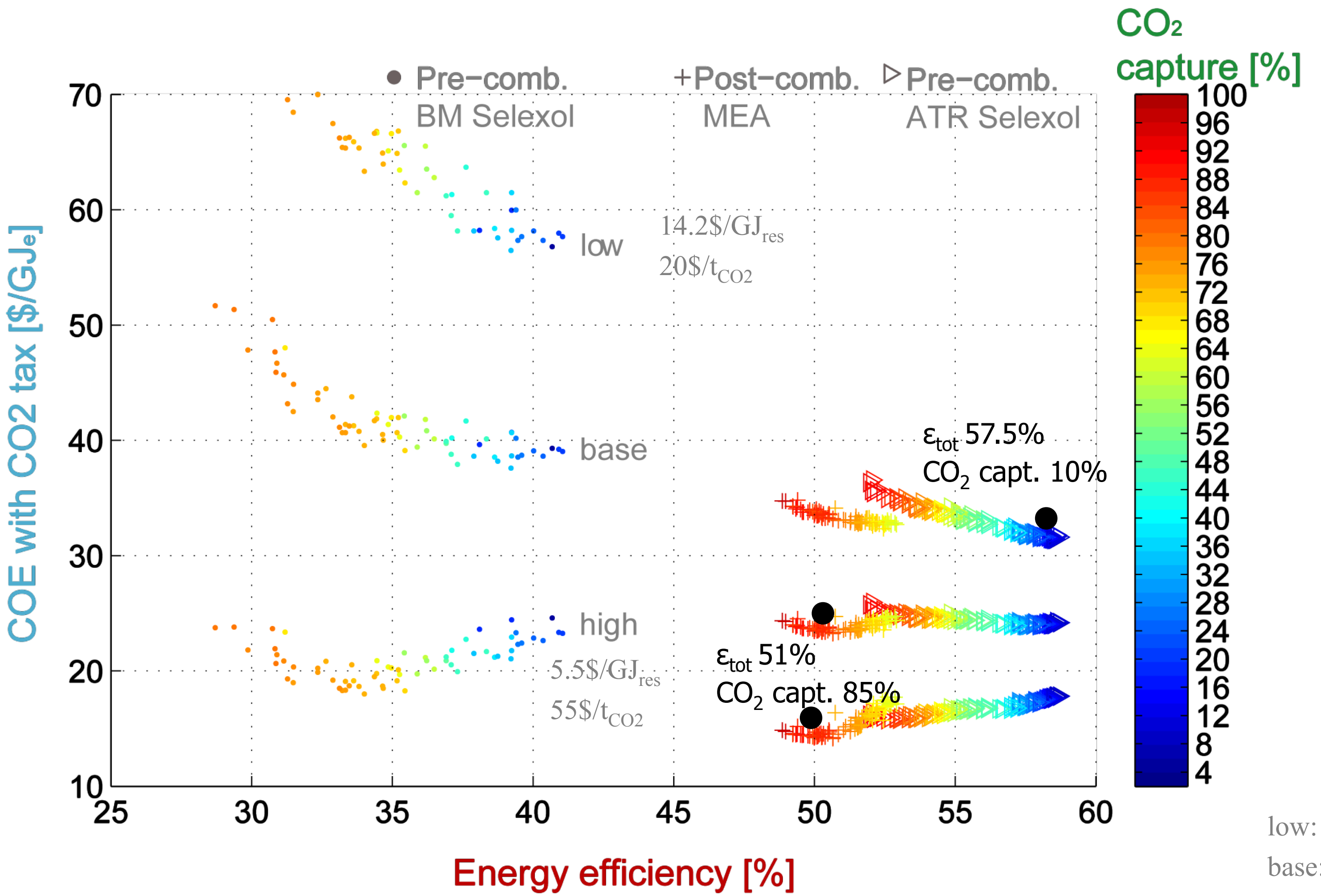
◆ CO_2 capture cost penalty



- ➢ Resource purchase
  - up to 80% of COE
- ➢ Competitiveness
  - Carbon tax
  - Economic conditions

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

- Economic competitiveness of process configurations
  - Influenced by economic conditions



- Strategy for supporting decision-making?

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

Most economically competitive process configurations

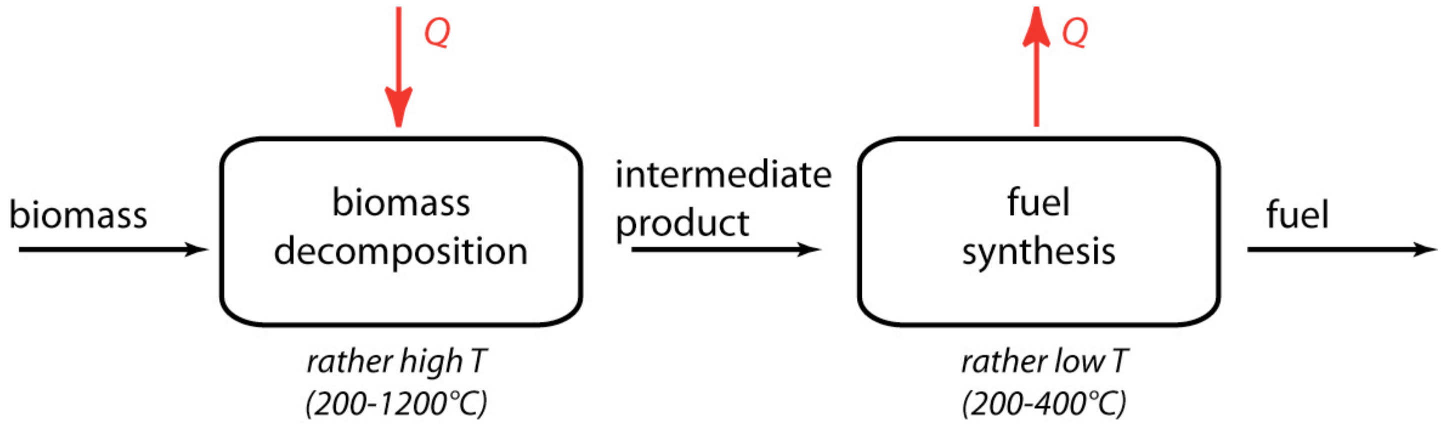
System	NGCC	Post-comb	ATR	BM
Performance	**no CC**	**MEA**	**Selexol**	**Selexol**
Feed [MW_{th}]	*559*	*582*	*725*	*380*
CO_2 capture [%]	*0*	*82.9*	*78.6*	*69.9*
ε_{tot} [%]	*58.75*	*50.6*	**53.5**	*35.4*
Net electricity [MW_e]	*328*	*295*	*383*	*135*
[$kg_{CO2, local}/GJ_e$]	*105*	*13.9*	*22.2*	**-198.1**
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 (CO₂ 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!

Thermochemical biomass conversion

Principle of conventional thermochemical routes

Thermochemical biomass to fuel reforming proceeds typically in two (or more) reaction steps:



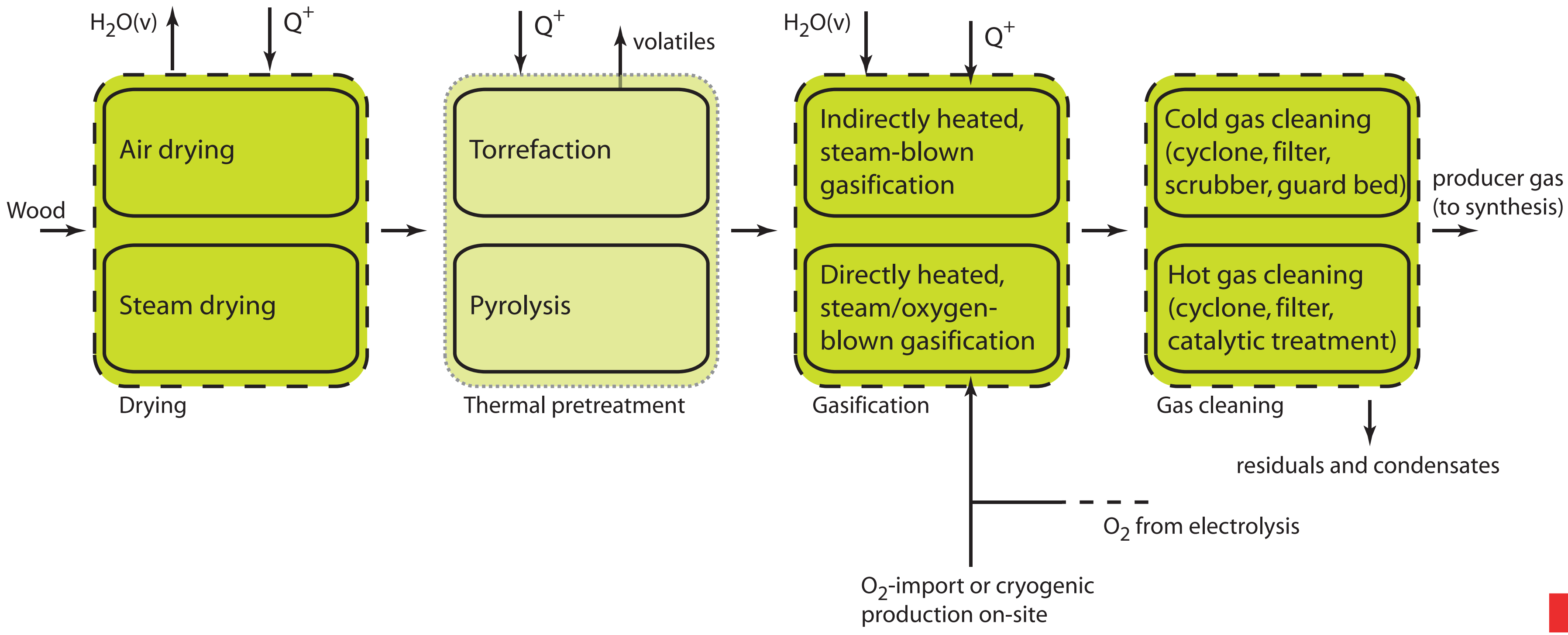
- gasification
- pyrolysis

non-condensable/ condensable substances (H_2, CO, CO_2, H_2O, CH_4, C_xH_y, char, tars)

- methanation
- FT synthesis
- DME synthesis
- methanol synthesis

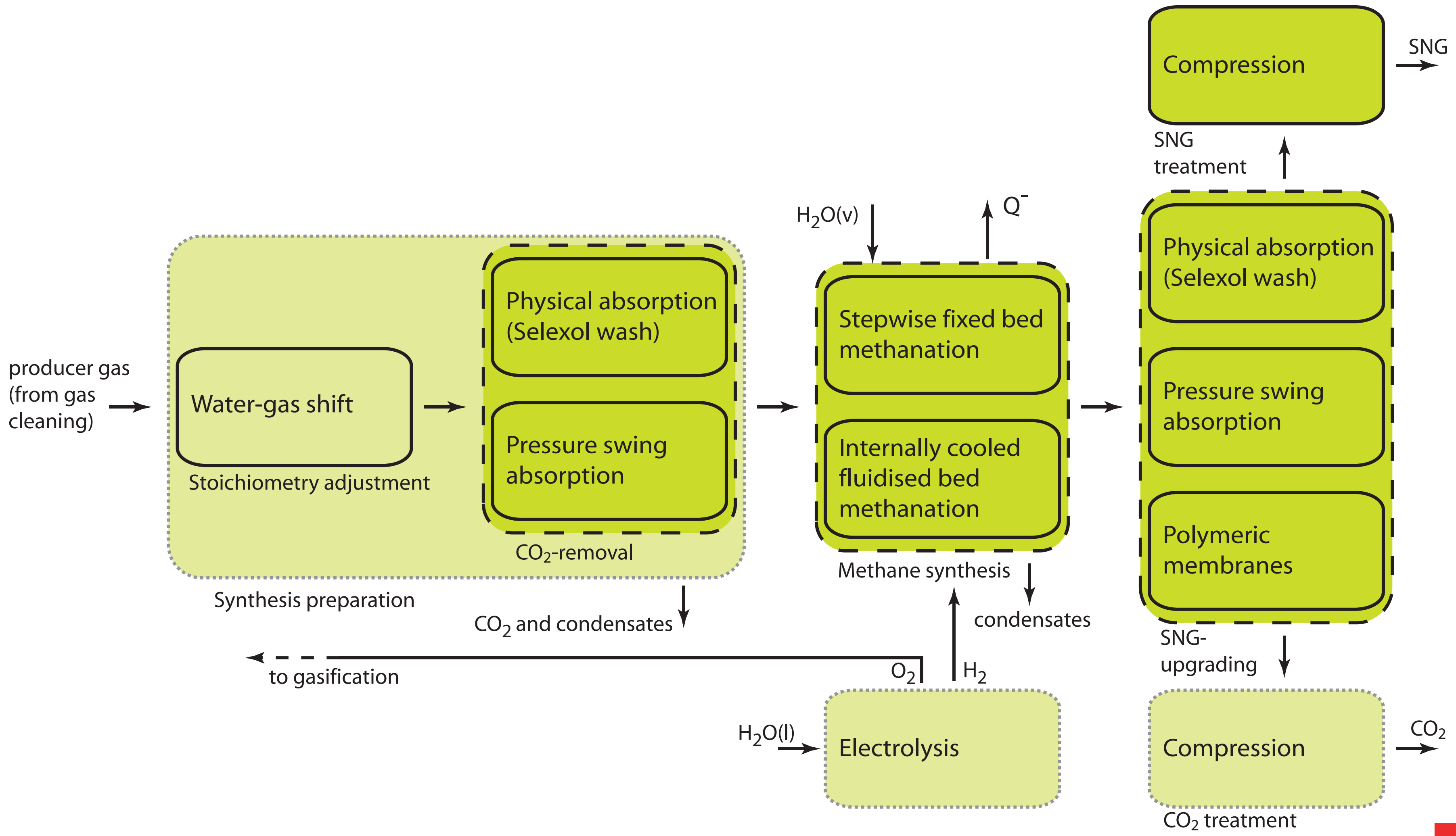
Block flow superstructure

Conventional route (gasification & methanation): decomposition



$$CH_{1.35}O_{0.63} + 0.3475H_2O \xrightarrow{\Delta H^0 = -10.5\ kJ/mol_{wood}} 0.51125CH_4 + 0.48875CO_2$$

Block flow superstructure
Conventional route (gasification & methanation): synthesis



$$CH_{1.35}O_{0.63} + 0.3475H_2O \xrightarrow{\Delta H^0 = -10.5\ kJ/mol_{wood}} 0.51125CH_4 + 0.48875CO_2$$

Gasification unit models

Problem set-up

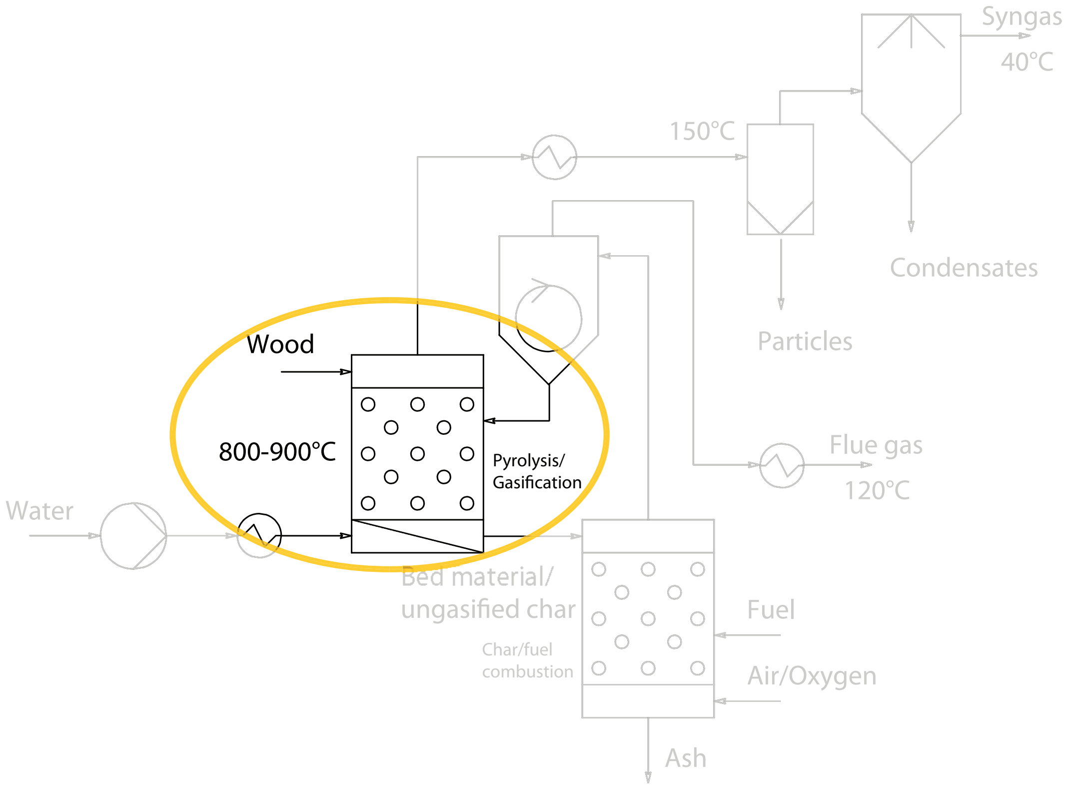
Gasification modelling problem:

- 8 bulk species:

  CH_4, CO, CO_2, H_2, H_2O, N_2, C_2H_4, $C(s)$

- 4 atomic mass balances

$\Rightarrow$ 4 model equations required



- 3 adjusted equilibrium equations

$$\hat{K}_{p,i} = K_{p,i}(T_g + \Delta T_i)$$

where: T_g gasification temperature
ΔT_i artificial temperature difference

- constant ratio between CH_4 and higher hydrocarbons

$$p_{C2H4} = k_p \cdot p_{CH4}$$

		Δh_r^0
hydrogenating gasification	$C(s) + 2H_2 \rightleftharpoons CH_4$	-75 kJ/mol
Boudouard equilibrium	$C(s) + CO_2 \rightleftharpoons 2CO$	173 kJ/mol
water-gas shift	$CO + H_2O \rightleftharpoons CO_2 + H_2$	-41 kJ/mol

Model reconciliation

Gas composition (%vol) & model constants

Process	FICFB		Viking		
Reactor	gasification		pyrolysis	gasification	
State	wet	dry	wet	wet	dry
CH_4	8.8 / 9.0	- / 9.3	- / 35.7	- / 1.2	1.2 / 1.2
CO	29.4 / 28.0	- / 28.9	- / 3.0	- / 18.3	19.6 / 19.0
CO_2	16.2 / 15.3	- / 15.9	- / 33.2	- / 14.2	15.4 / 14.7
H_2	37.3 / 39.5	- / 41.0	- / 4.9	- / 30.4	30.5 / 31.4
H_2O	3.6 / 3.5	- / -	- / 23.0	- / 3.2	- / -
N_2	2.9 / 2.9	- / 3.0	- / 0.2	- / 32.7	33.3 / 33.7
C_2H_4	1.8 / 1.8	- / 1.9	- / -	- / -	- / -

measures (Rauch, R. (2004), Goebel, B. et al. (2004)) / calculation

⇒ accurate reproduction of gas composition & heat demand

Process	FICFB	Viking	
Reactor	gasification	pyrolysis	gasification
ΔT_{hg}	**-260°C**	-289°C	**-11°C**
ΔT_{bd}	**-201°C**	-	**-123°C**
ΔT_{wg}	**-112°C**	+12°C	**-126°C**
k_p	4.9	-	-

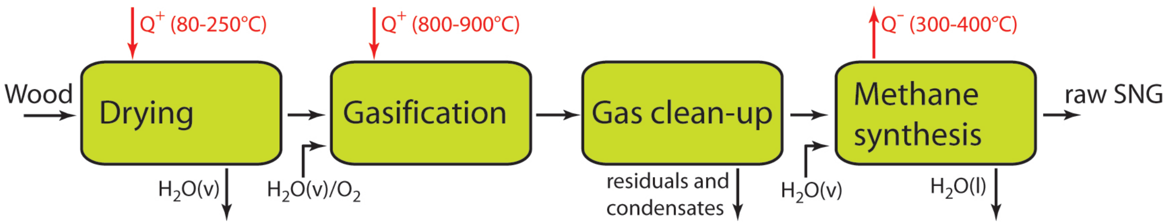
reconciled model constants

⇒ **part. oxidation at high T gets closer to equilibrium**

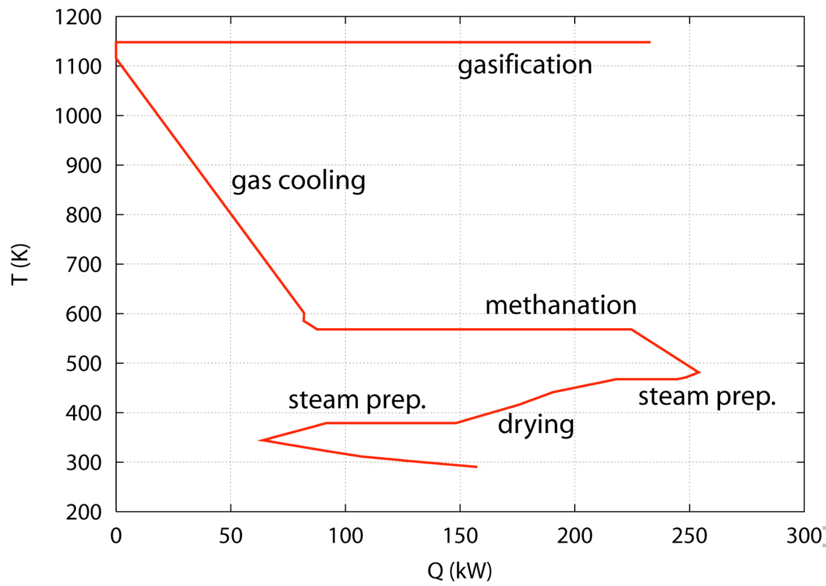
Flowsheet generation (2)

Energy-integration model

How to satisfy the MER?

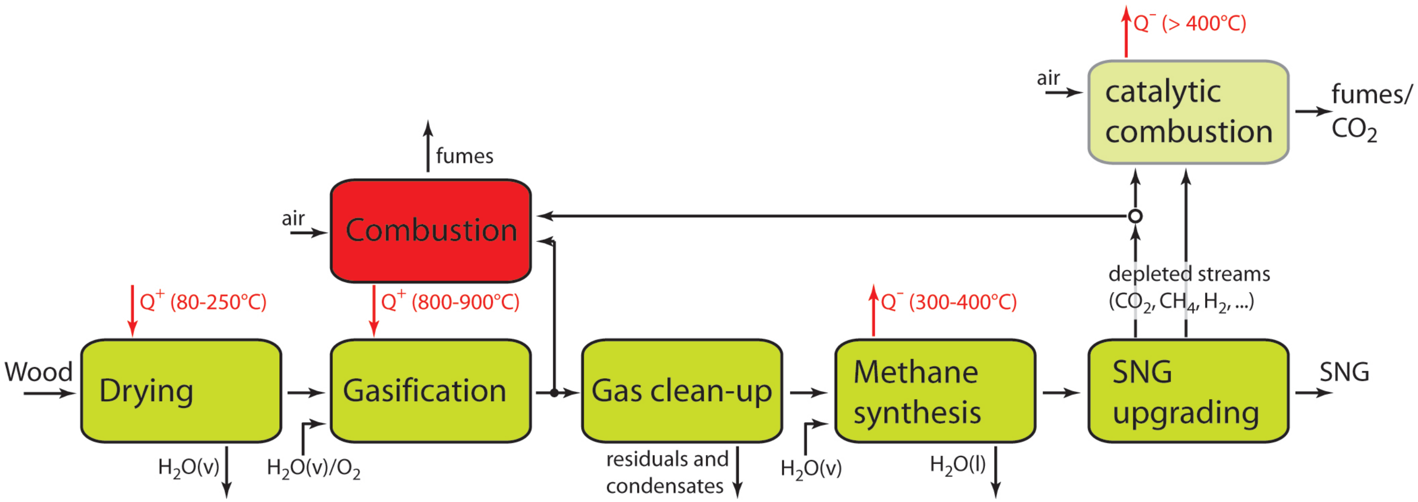


- MER of crude production

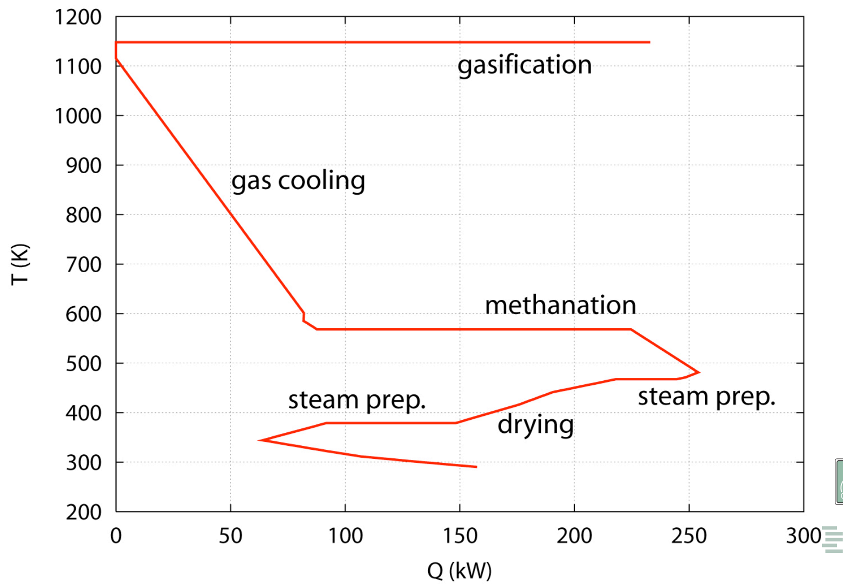


Flowsheet generation (2)
Energy-integration model

How to satisfy the MER?

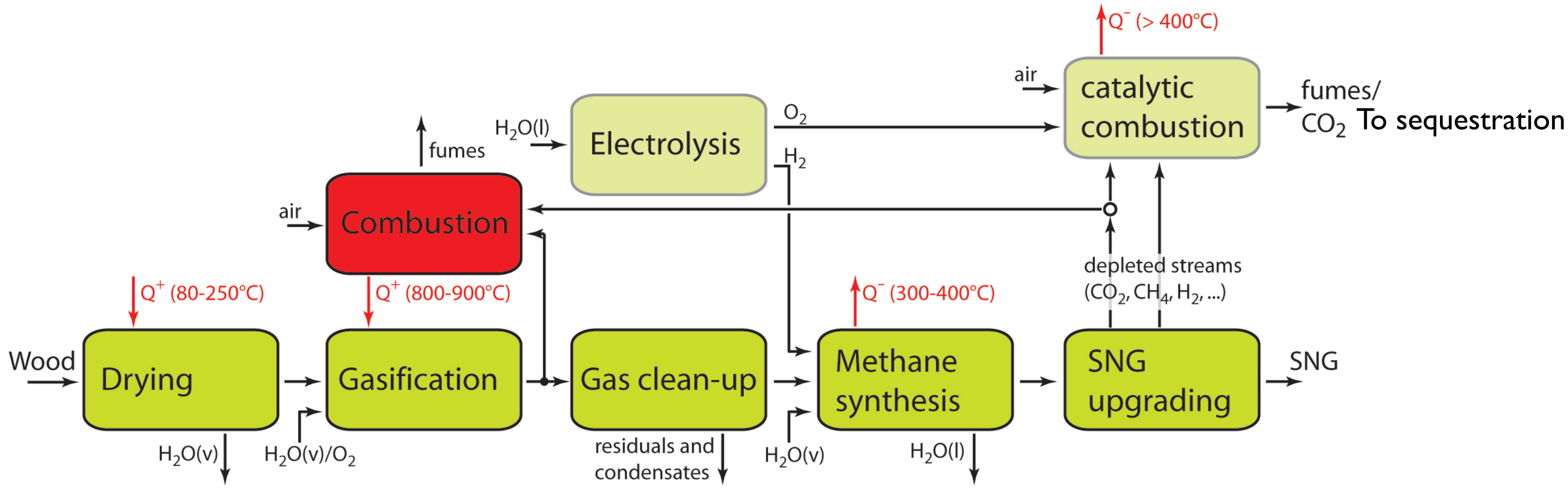


- MER of crude production
- hot utility: combustion
- fuel choice?
  - waste streams
  - intermediate products

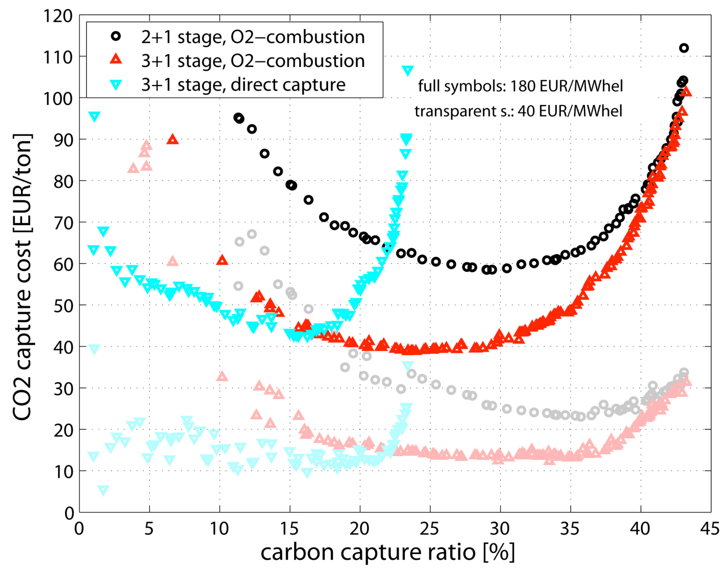


Flowsheet generation (2)
Energy-integration model

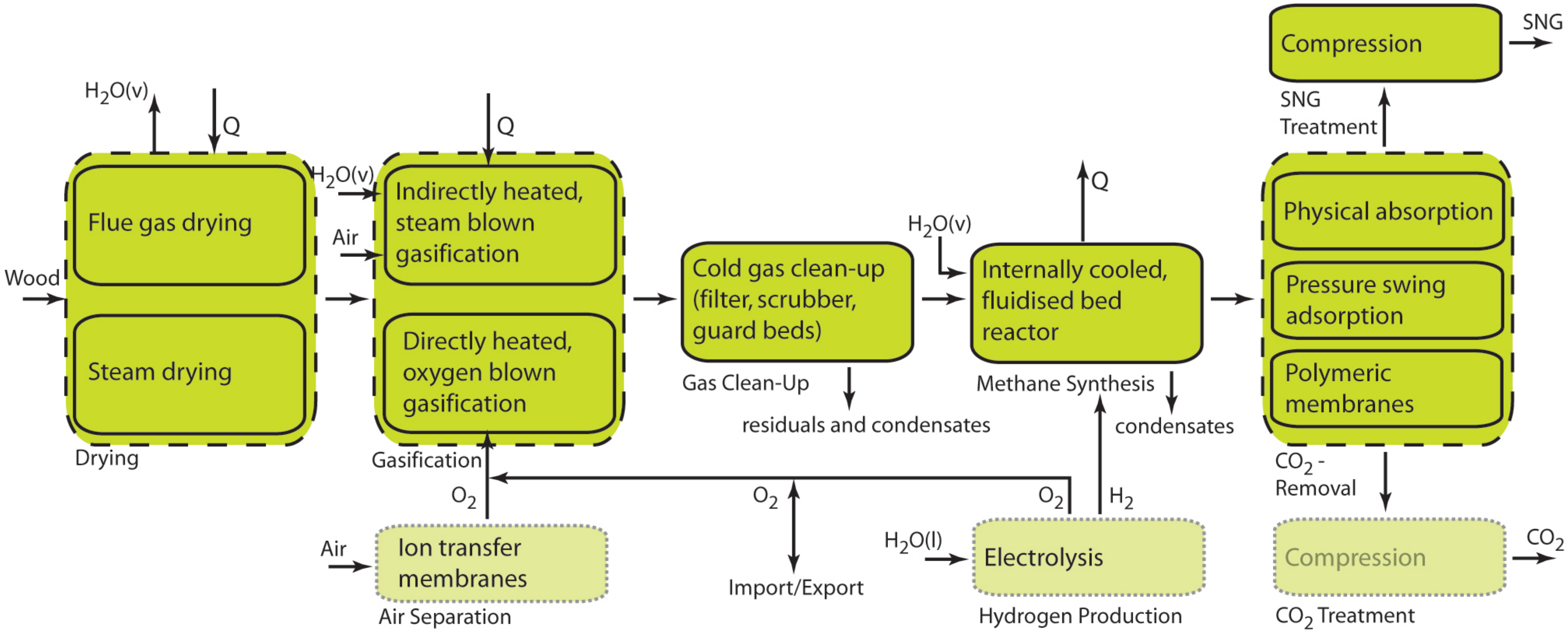
How to satisfy the MER (while by-producing pure CO_2)?



- MER of crude production
- hot utility: combustion
- fuel choice?
- perspective: CCS at < 15 €/t

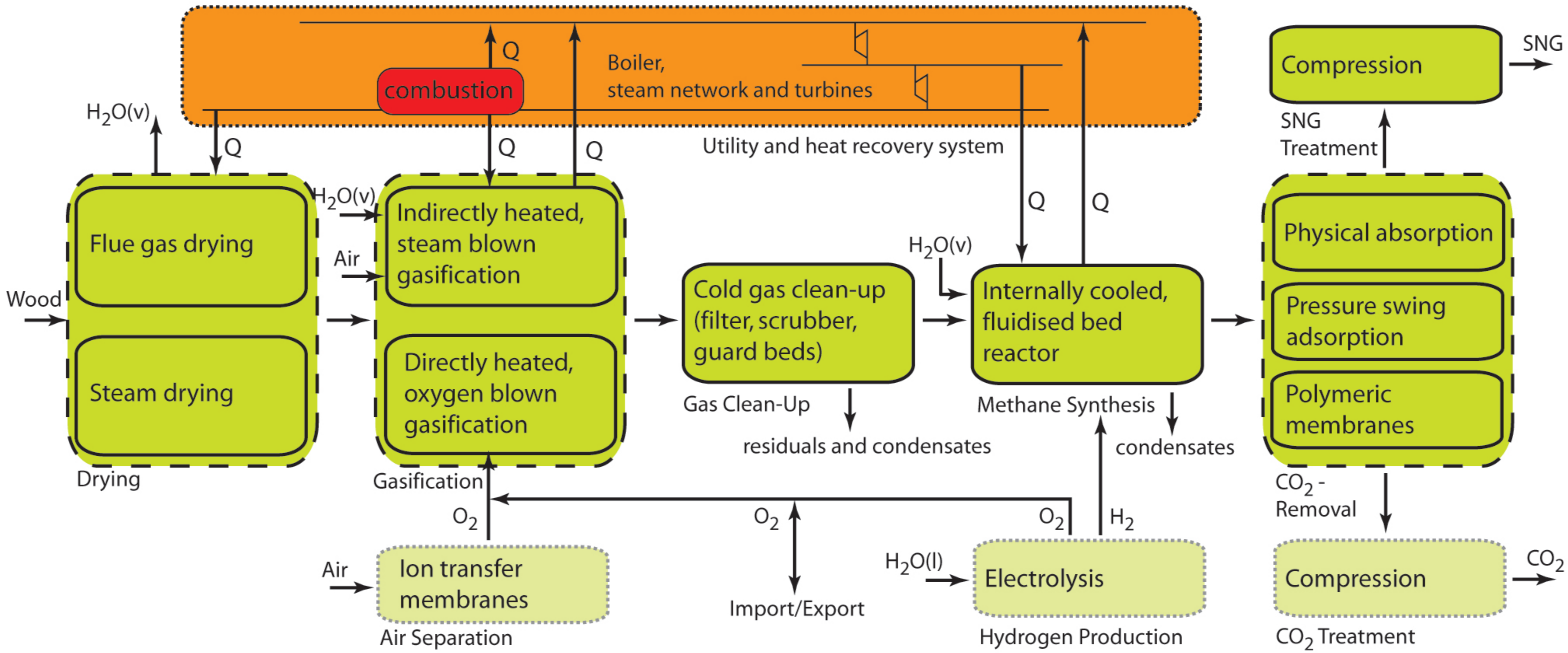


Integrating heat recovery technologies in the superstructure



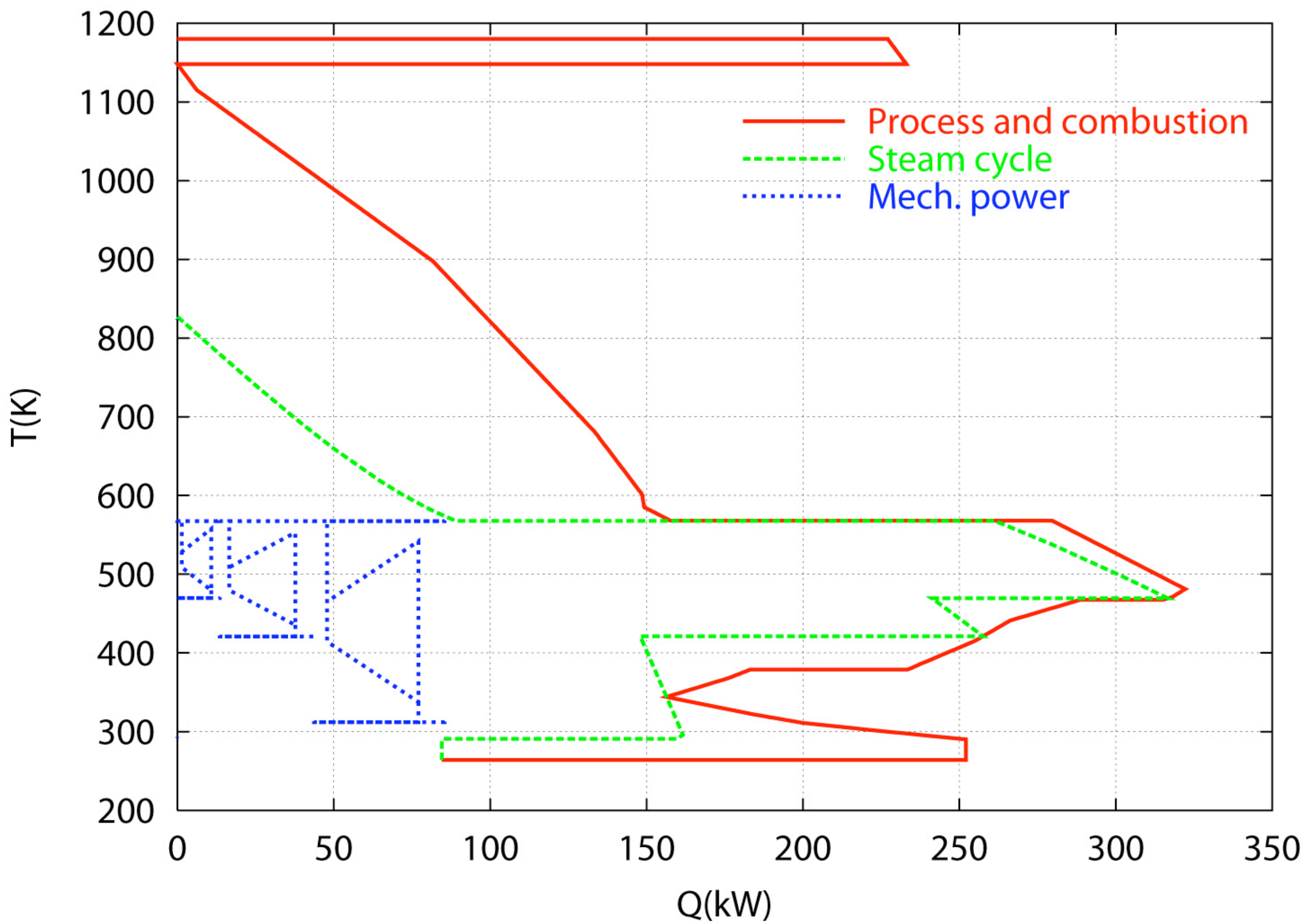
Flowsheet generation (2)
Energy-integration model

Integrating heat recovery technologies in the superstructure



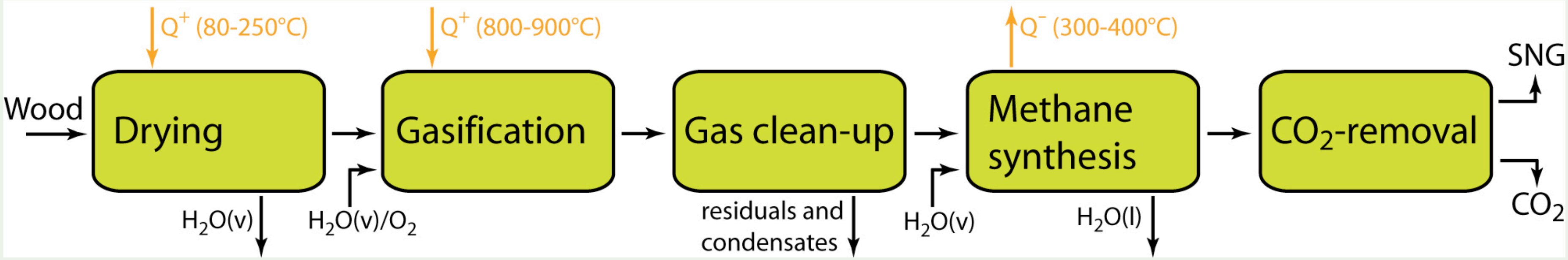
Flowsheet generation (2)
Energy-integration model

MILP resolution: ... to an integrated solution



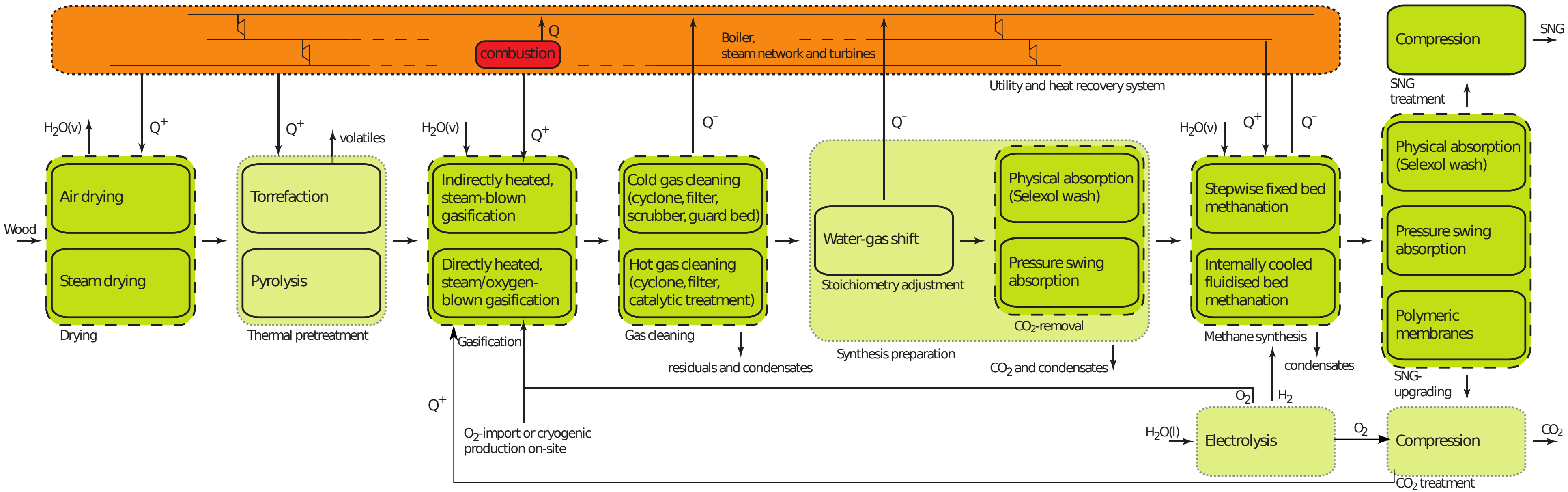
BIOSNG process design

Example: Common wood to SNG route

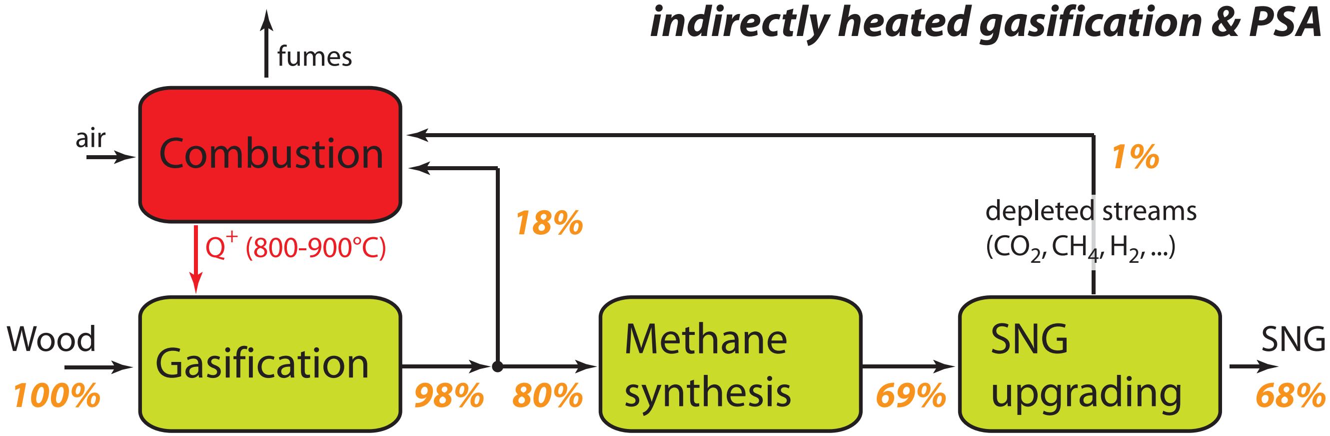


$$CH_{1.35}O_{0.63} + 0.3475H_2O \xrightarrow{\Delta H^0 = -10.5\ kJ/mol_{wood}} 0.51125CH_4 + 0.48875CO_2$$

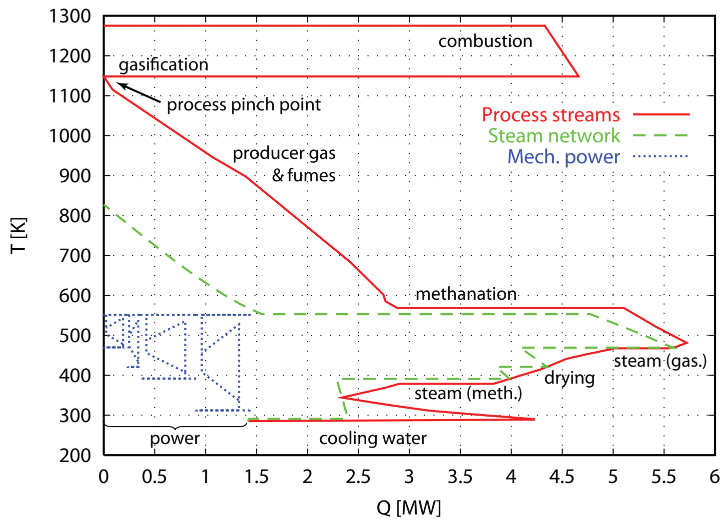
Process superstructure



Some (non-optimised) scenarios for conventional SNG production:



(only the chemical energy flow of the main product conversion is shown)

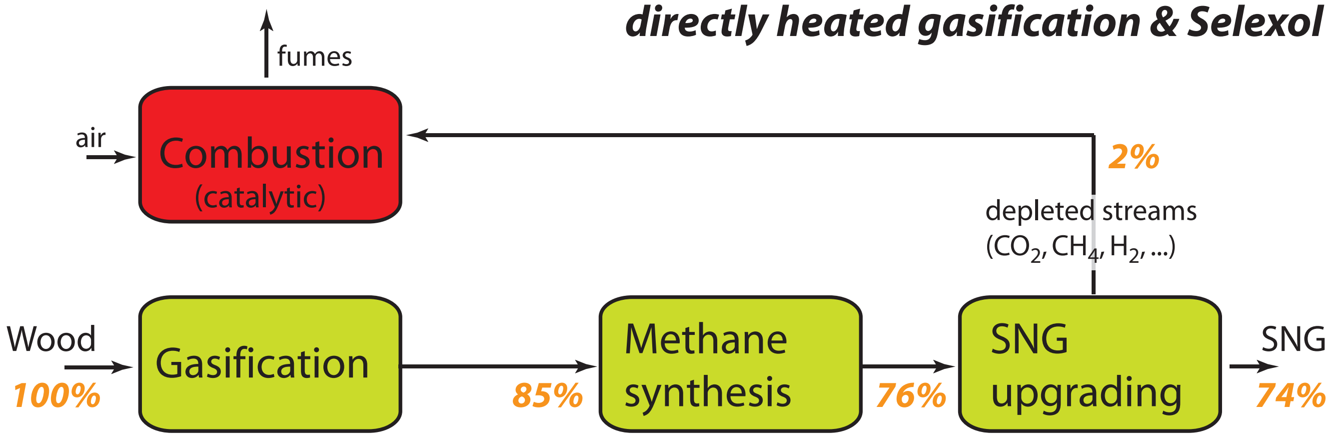


input: 20 $MW_{th,wood}$

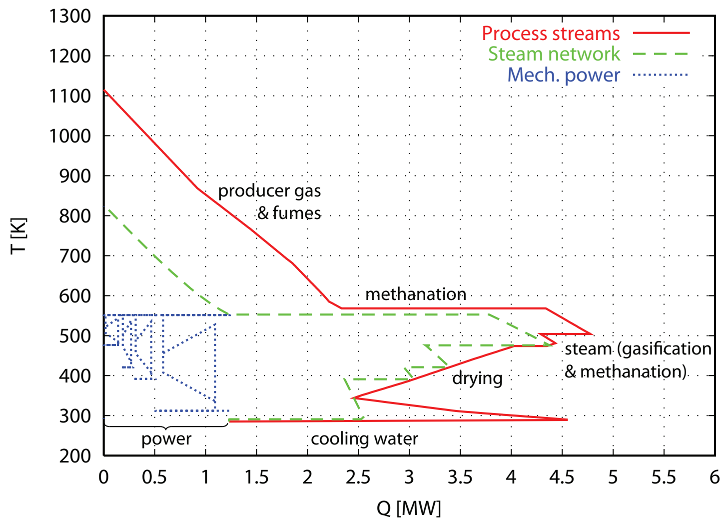
		FICFB				CFB	
		(base)	(torr)	(pM)	(pM, SA)	(pGM)	(pGM, hot)
Consumption	Wood	100%	100%	100%	100%	100%	100%
	Biodiesel	1.8%	1.6%	1.8%	1.8%	0.1%	-
	Electricity	-	0.5%	-	-	0.9%	-
Production	SNG	67.7%	72.1%	67.5%	67.8%	74.0%	74.0%
	Electricity	2.9%	-	2.6%	3.3%	-	1.6%
Overall efficiency		69.4%	70.7&	68.8%	69.8%	73.2%	75.6%

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Some (non-optimised) scenarios for conventional SNG production:



(only the chemical energy flow of the main product conversion is shown)



input: 20 $MW_{th,wood}$

		FICFB					CFB
		(base)	(torr)	(pM)	(pM, SA)	(pGM)	(pGM, hot)
Consumption	Wood	100%	100%	100%	100%	100%	100%
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	Electricity	-	0.5%	-	-	0.9%	-
Production	SNG	67.7%	72.1%	67.5%	67.8%	74.0%	74.0%
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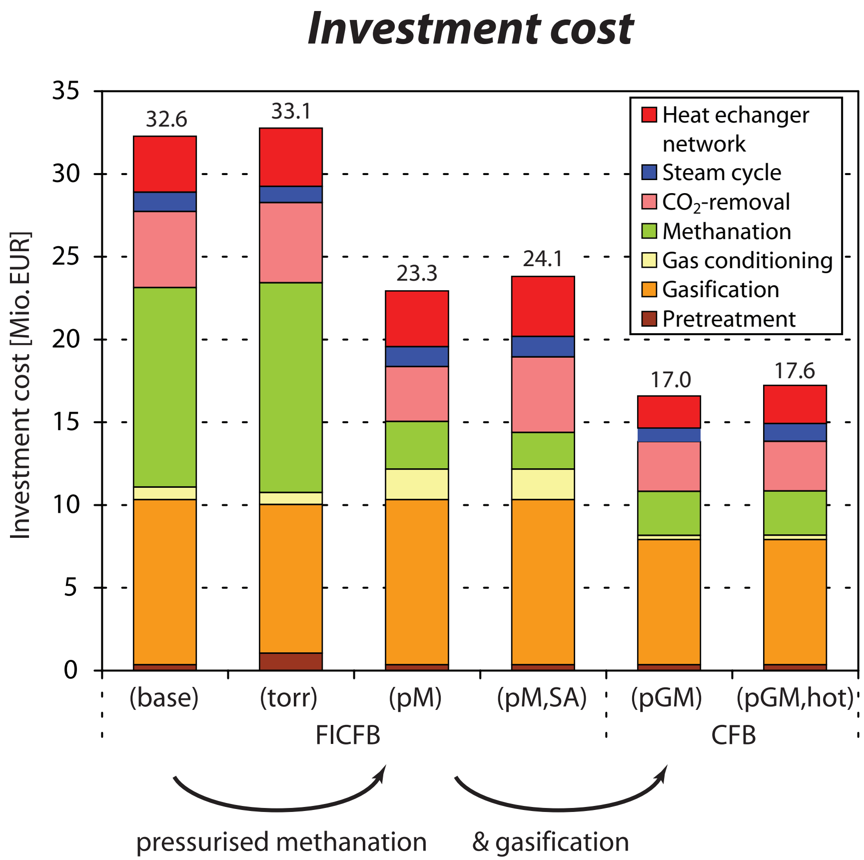

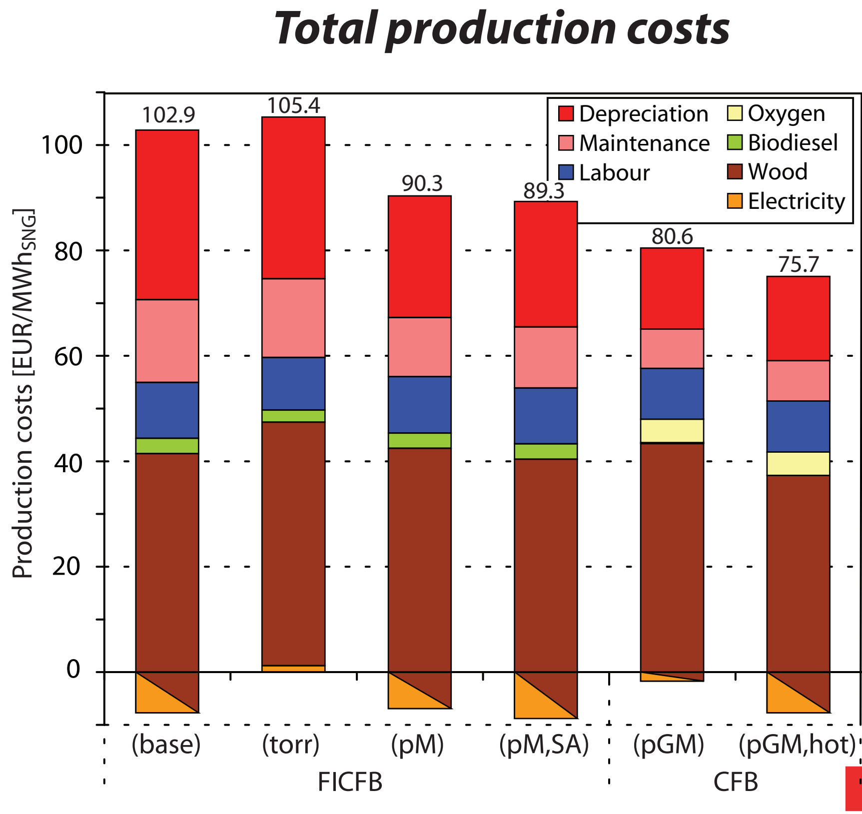

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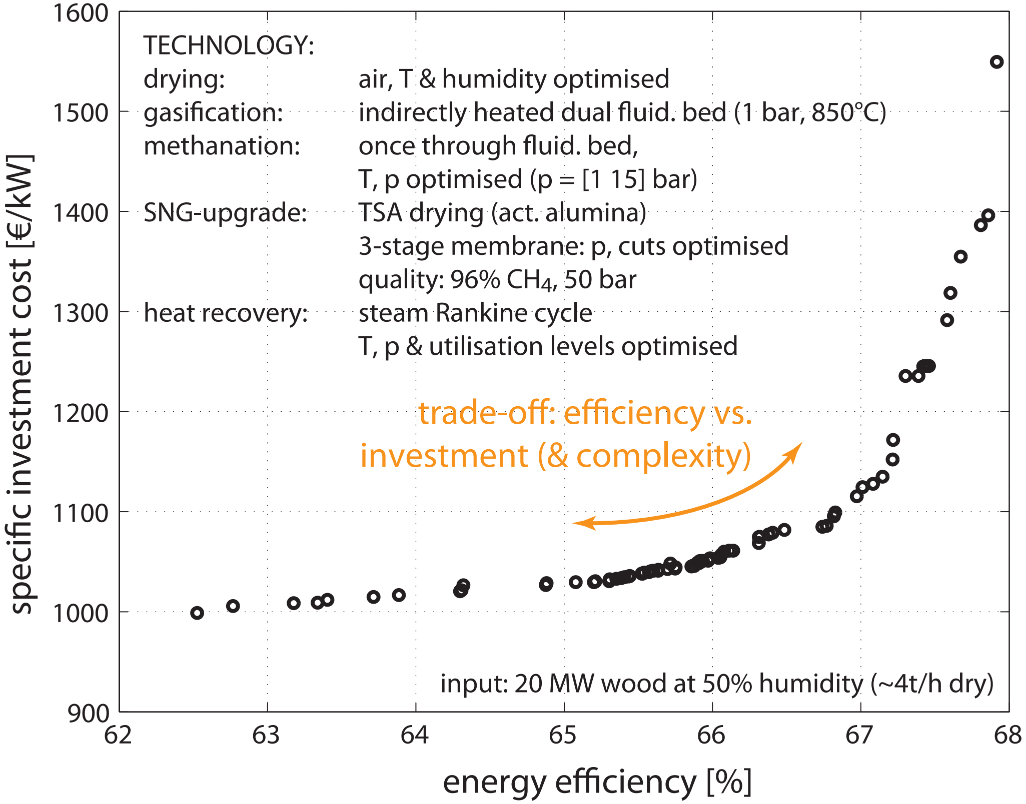
Thermo-economic optimisation

Trade-offs: efficiency and scale vs. investment

Efficiency vs. investment:



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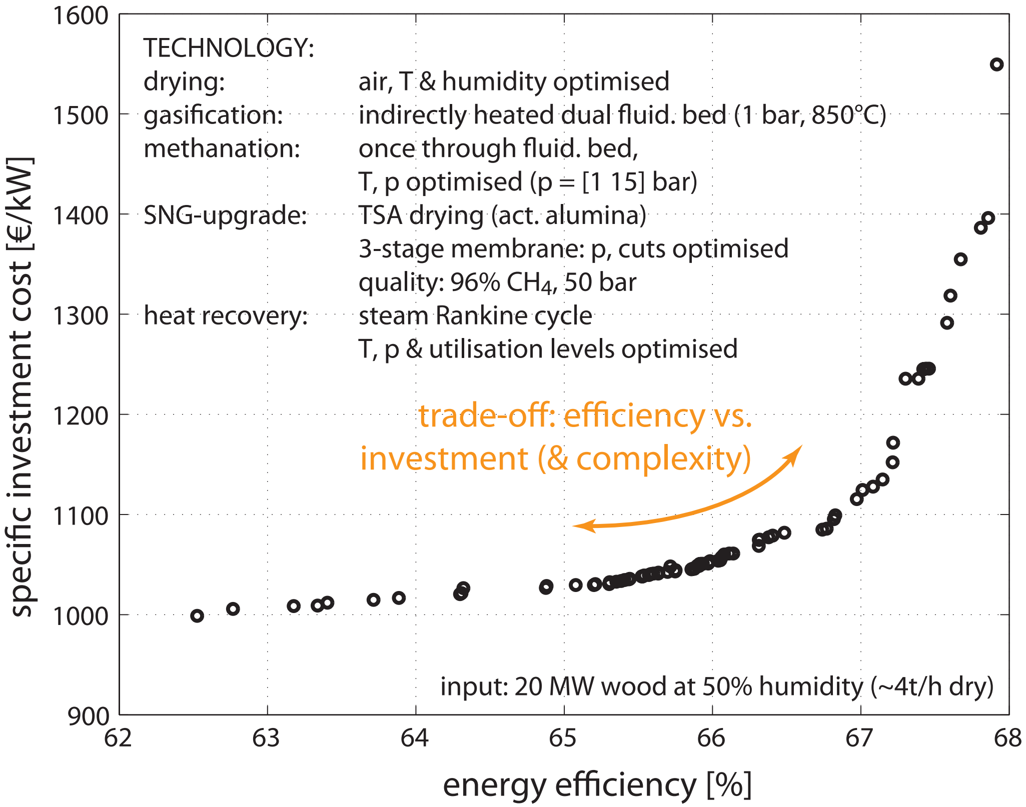
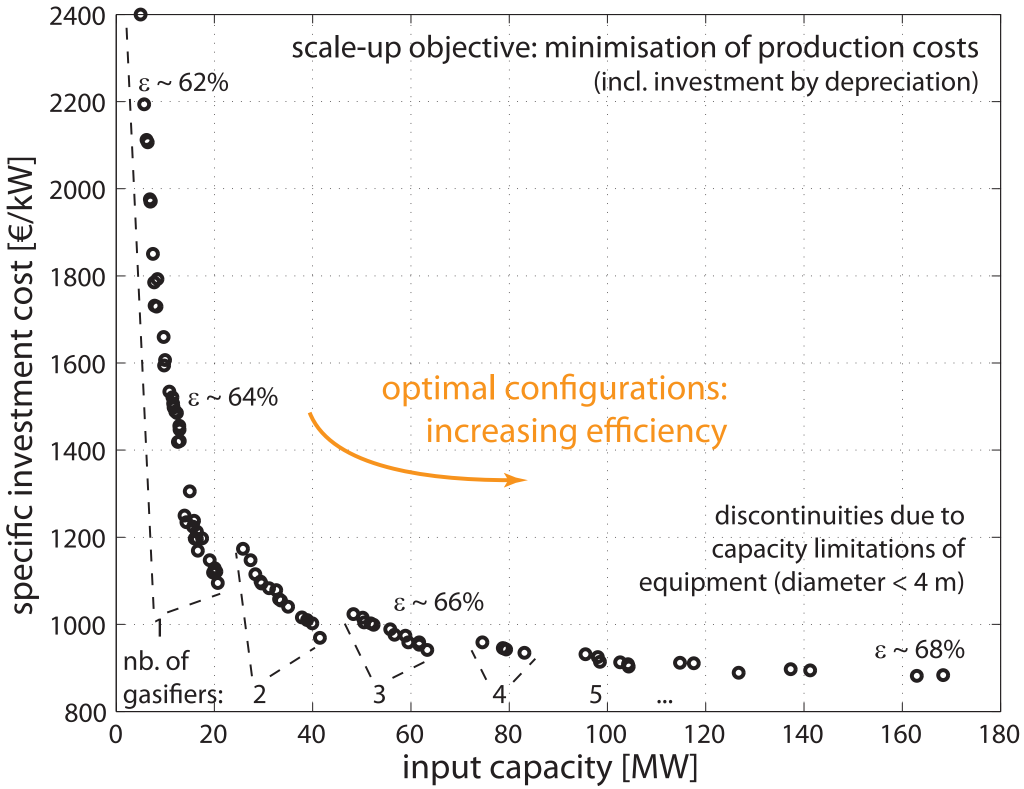
Thermo-economic optimisation

Trade-offs: efficiency and scale vs. investment

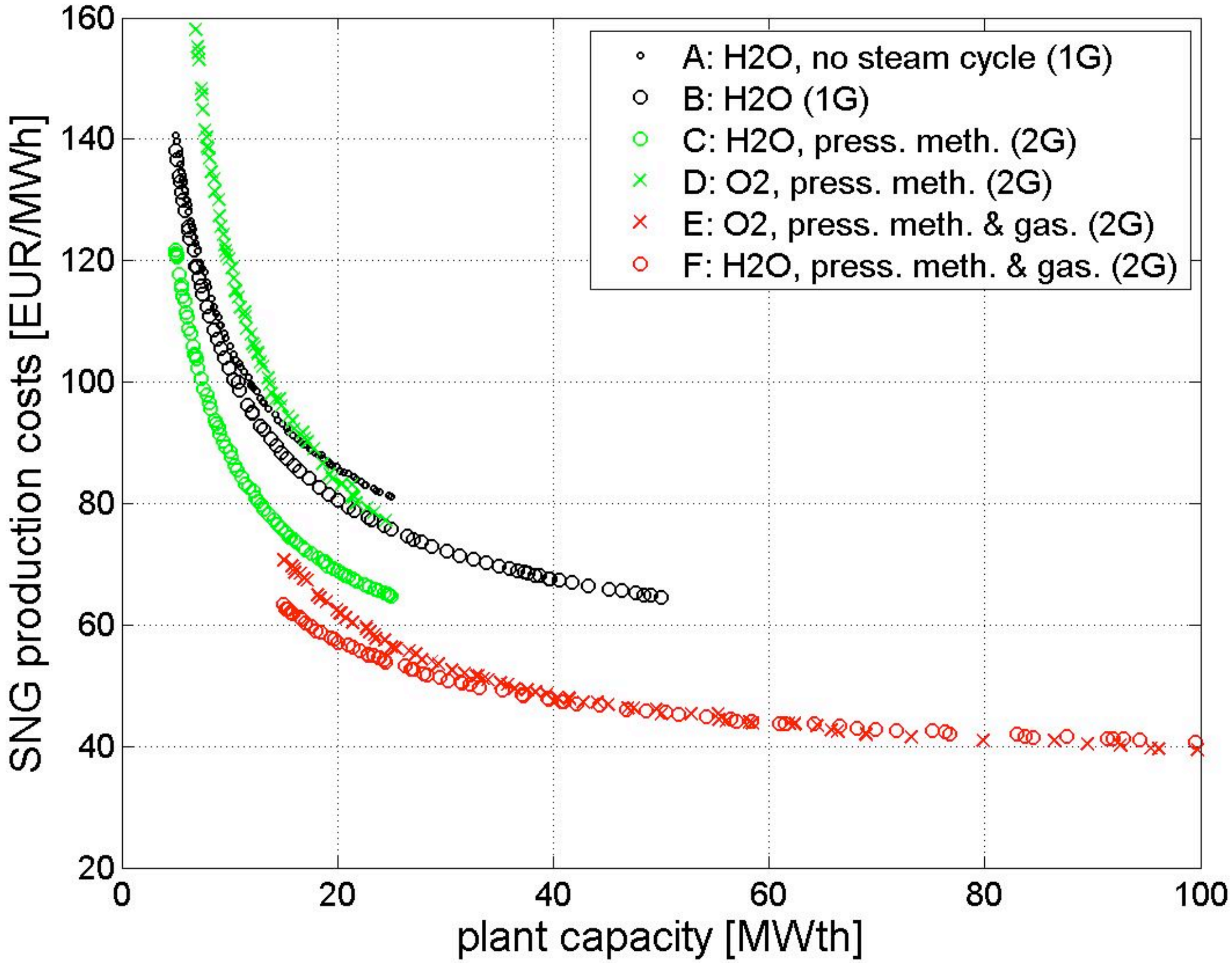
Efficiency vs. investment and optimal scale-up:





Comparing process configurations
Perspective: comparing process generations

Plant capacity vs. production costs



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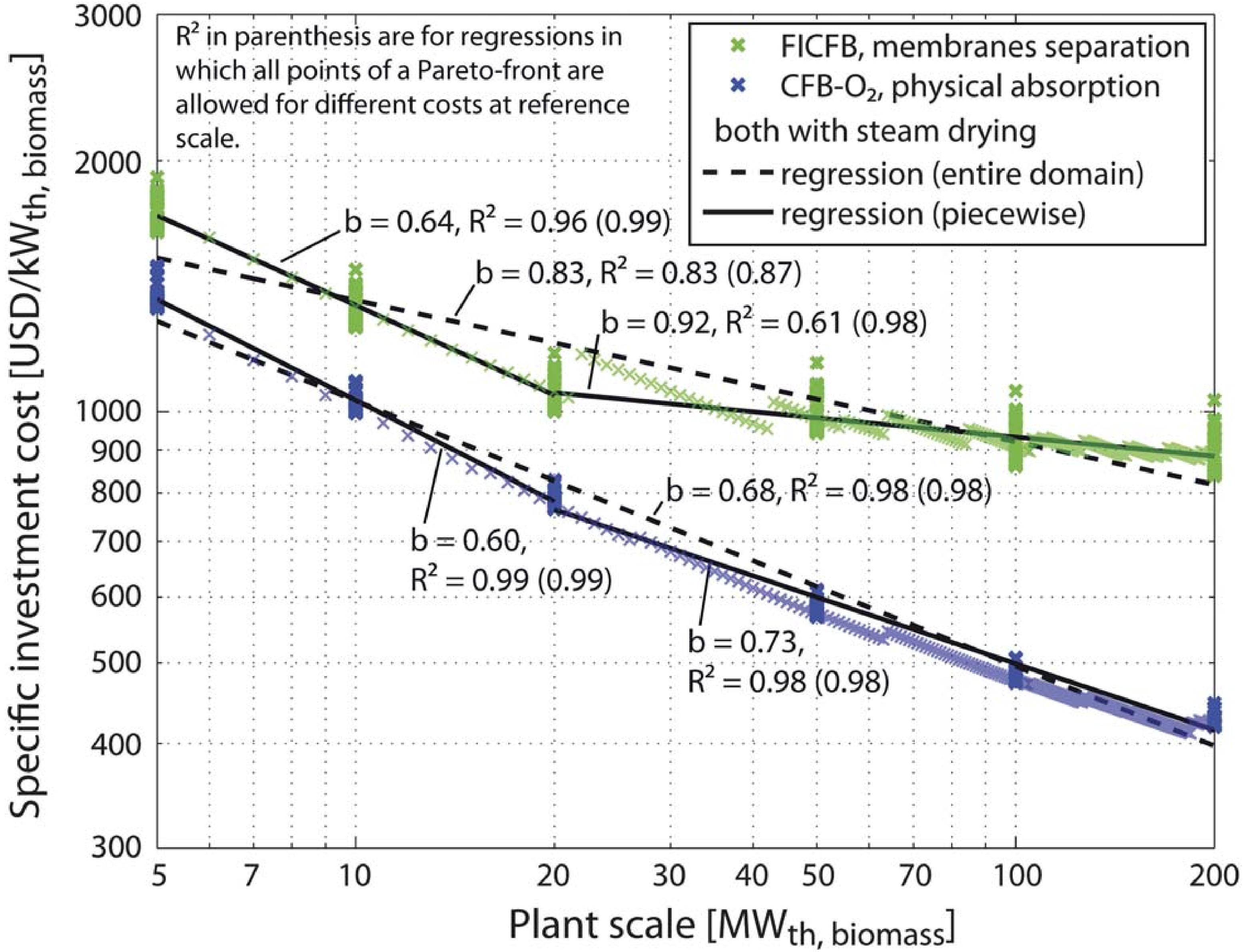
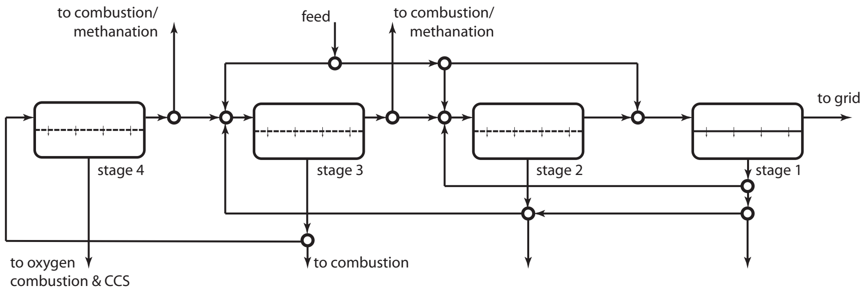
Investment as a function of biomass feed



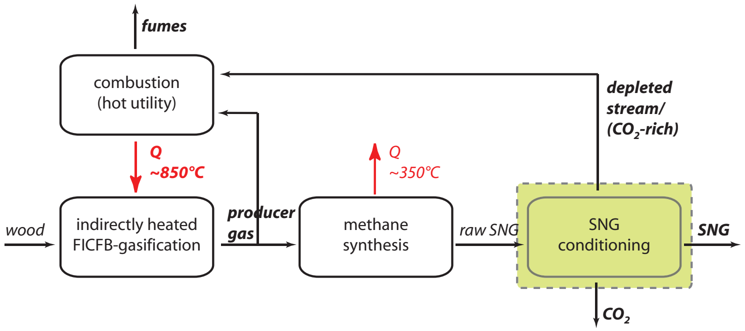
Technology integration example
Gas upgrading by membrane

Membrane system upgrading superstructure

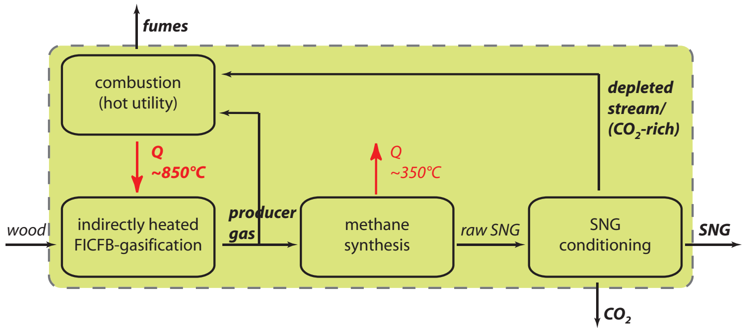
CH4/CO2 separation



"isolated": separation only



"integrated": total system



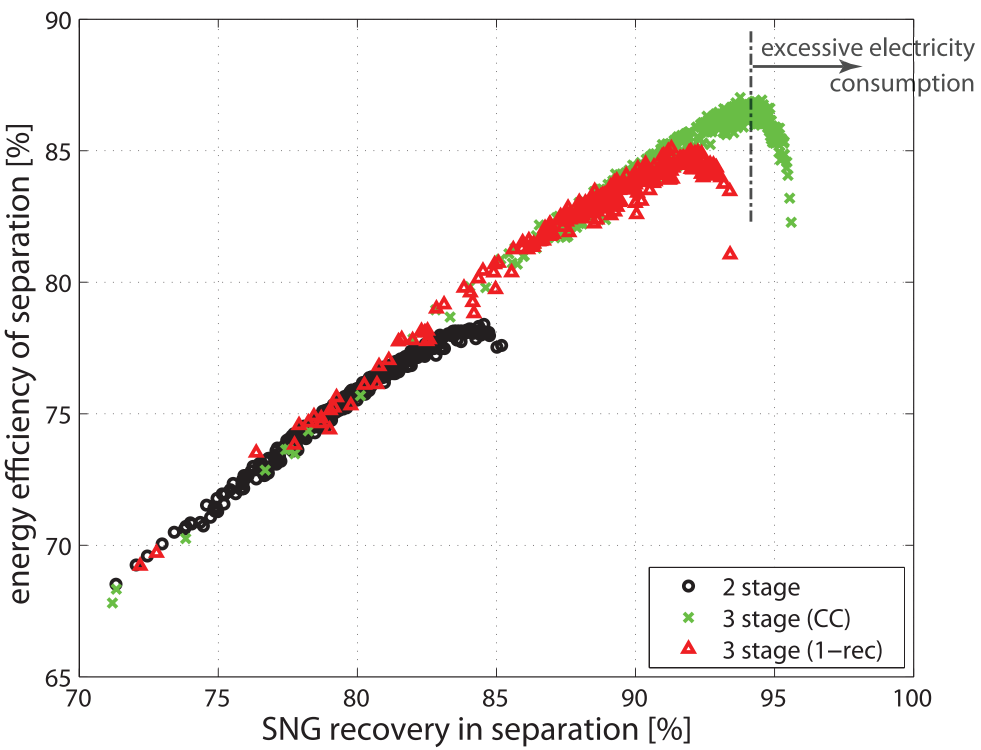
- Maximise SNG recovery
- Permeate stream is lost

- Permeate stream valorised
- Overall system performance

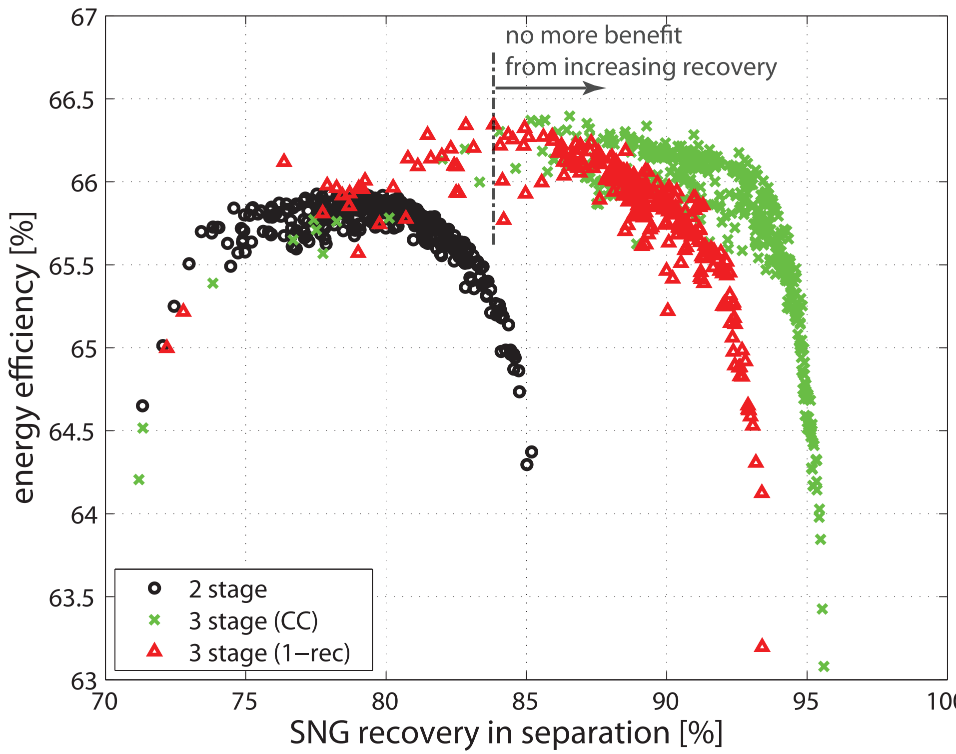
Technology integration example
Gas upgrading by membrane

Energy efficiency:

separation only



total system



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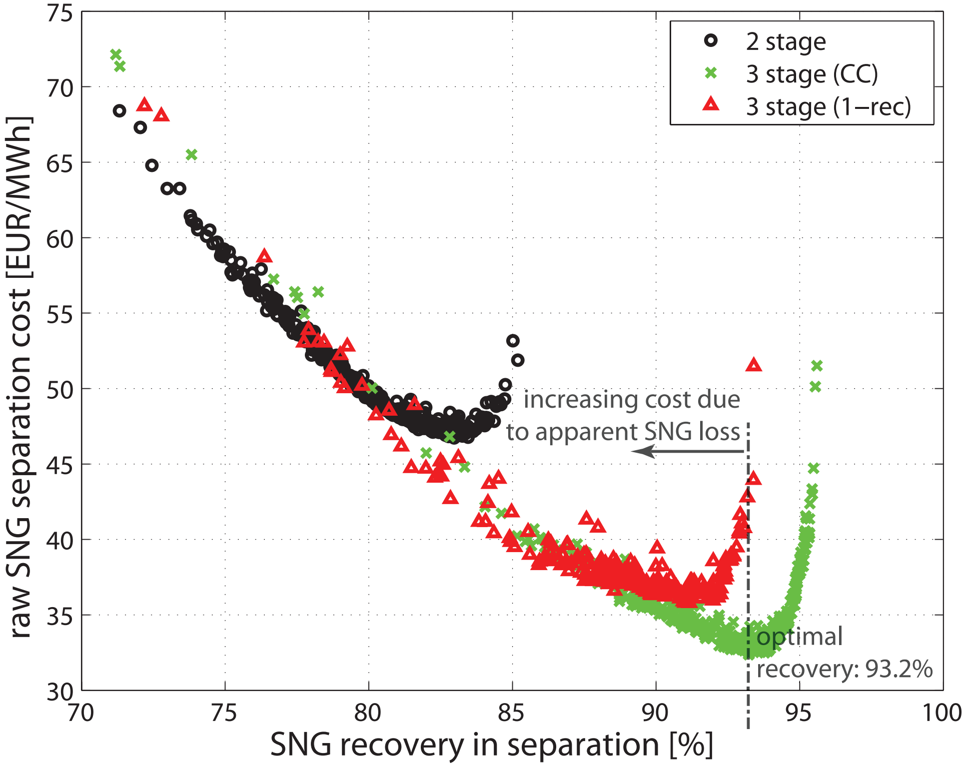
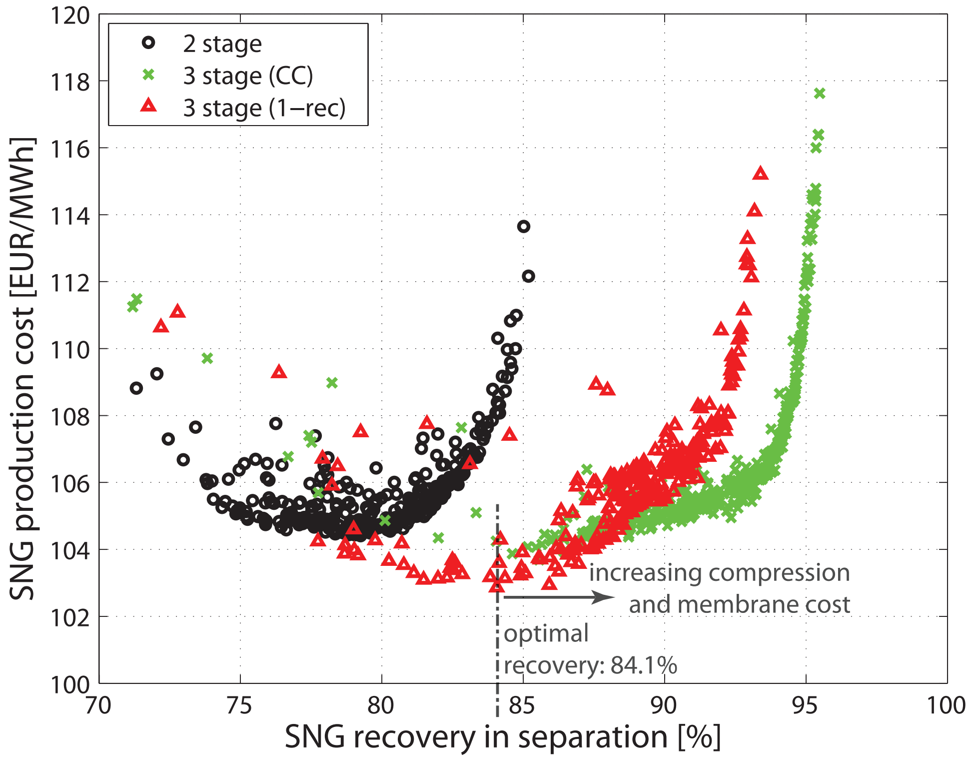
Production costs:

separation only



total system



Technology integration example

Gas upgrading by membrane

Results : Isolated vs integrated design

		isolated	integrated	overshoot
system		**3-stage CC**	**3-stage, 1 rec**	
r_{SNG}	%	**93.2**	**84.1**	+ 10.8%
e_{spec}^{sep}	$kW_{el}/MW_{th,in}$	**76.9**	**55.9**	+ 37.6%
$\tilde{c}_{CO2,p}$	%	86.6	79.9	+ 8.4%
$\tilde{c}_{H2,p}$	%	10.3	9.4	+ 9.6%
$\tilde{c}_{CH4,p}$	%	3.0	10.4	− 71.2%
A	m^2	**4675**	**2928**	+ 59.7%
C_I^{sep}	M€	**5.7**	**4.1**	+ 39.0%
ϵ^{sep}	%	86.6	80.7	+ 8.8%
ϵ_{cg}	%	69.0	63.5	+ 8.7%
ϵ	%	66.0	66.2	− 0.3%
C_I	M€	30.7	29.9	+ 2.7%
C_P	€/MWh	105.6	102.9	+ 2.6%

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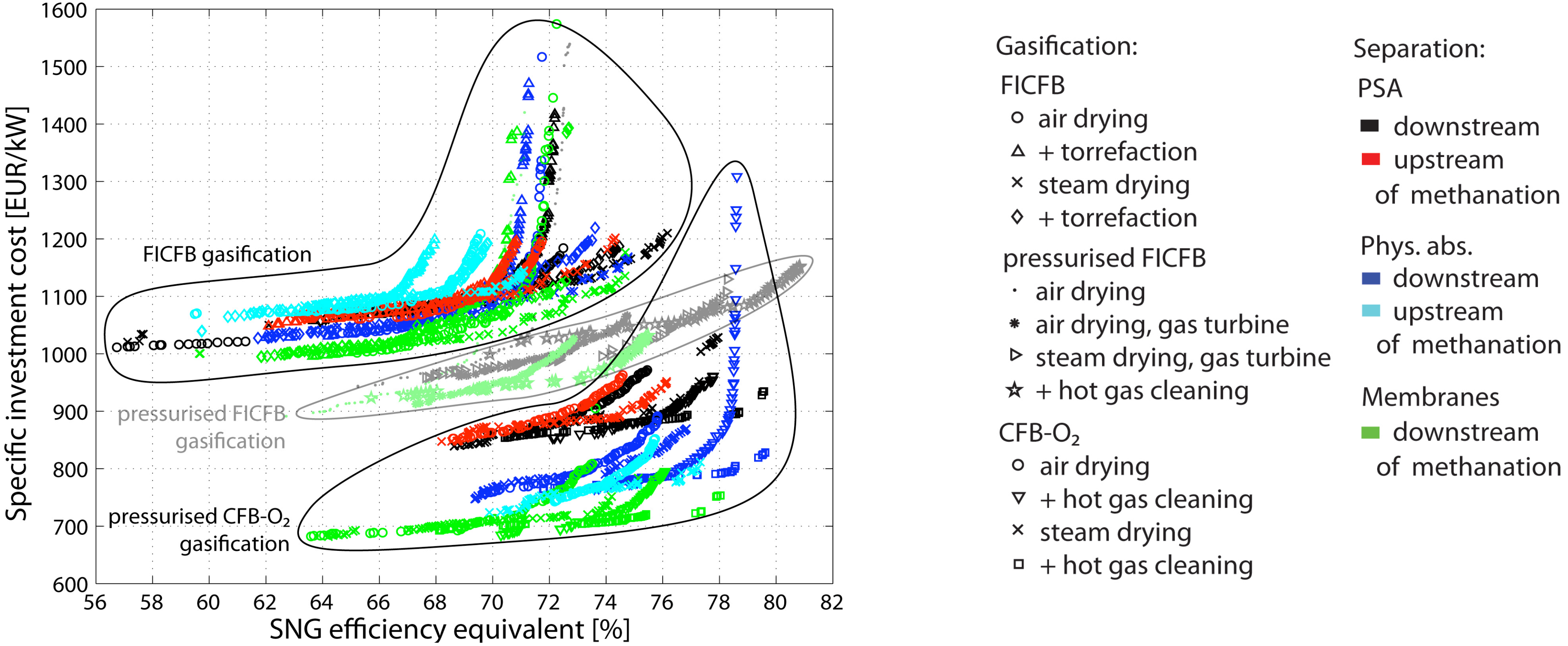
Comparing options

- Each point of the Pareto is a process design

Thermo-economic Pareto front (cost vs efficiency):

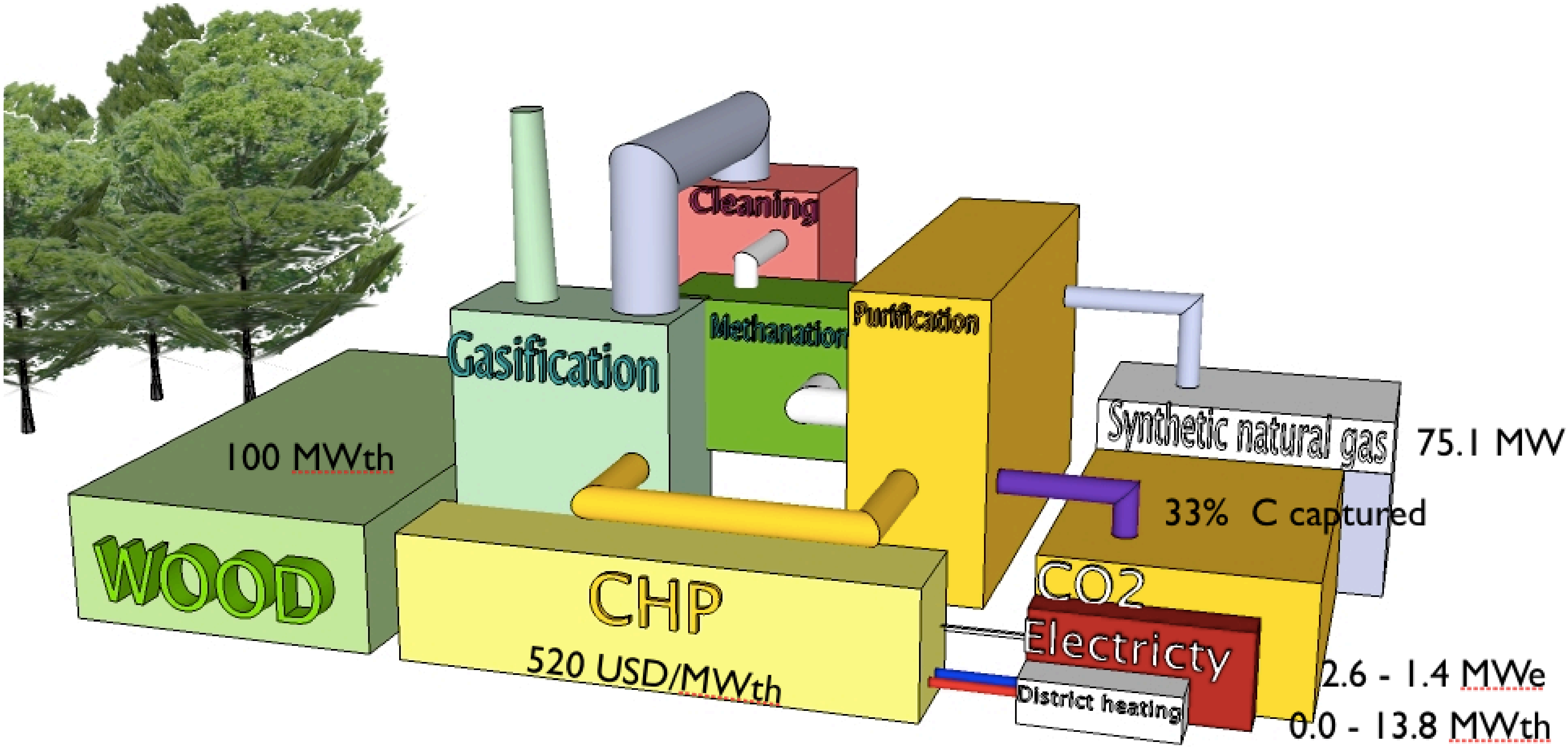


Note : 1.5 years of calculation time !

Gassner, Martin, and François Maréchal. *Energy & Environmental Science* 5, no. 2 (2012): 5768 – 5789.

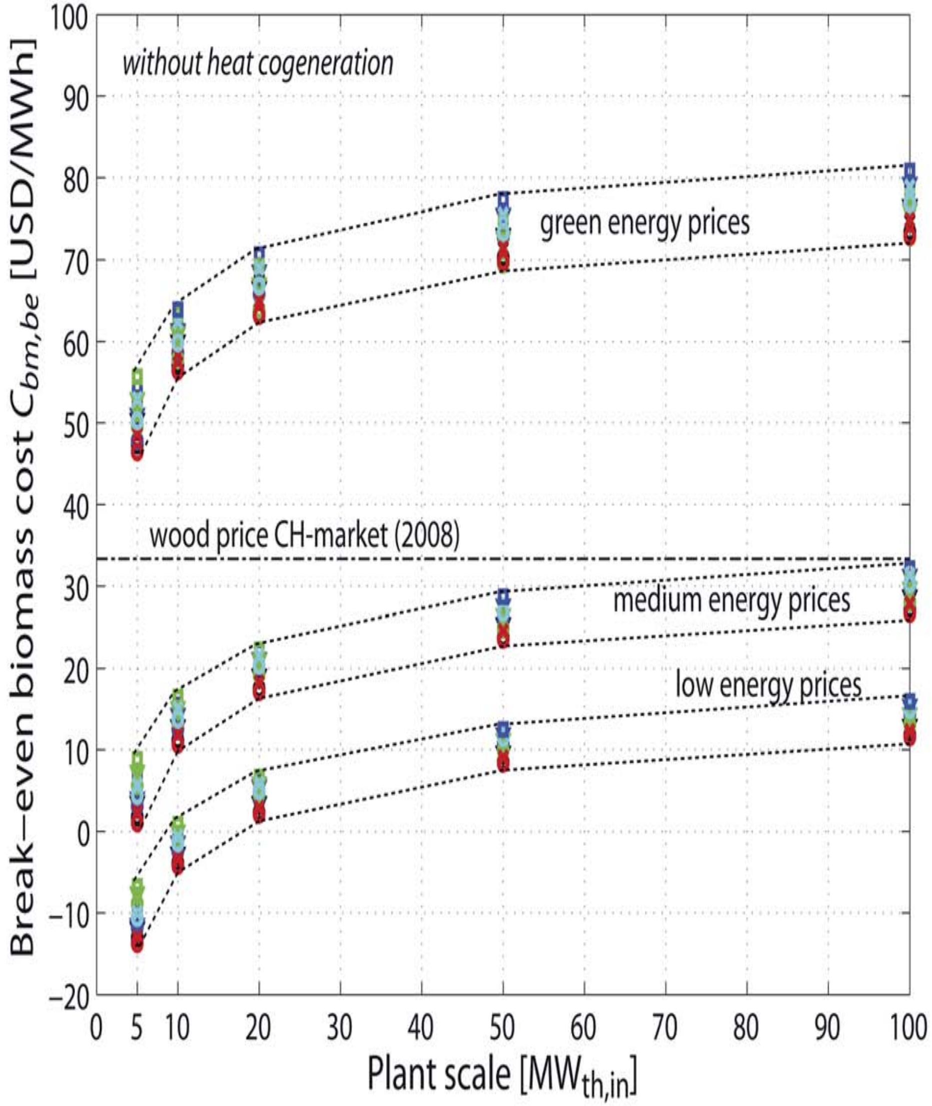
BIOSNG process

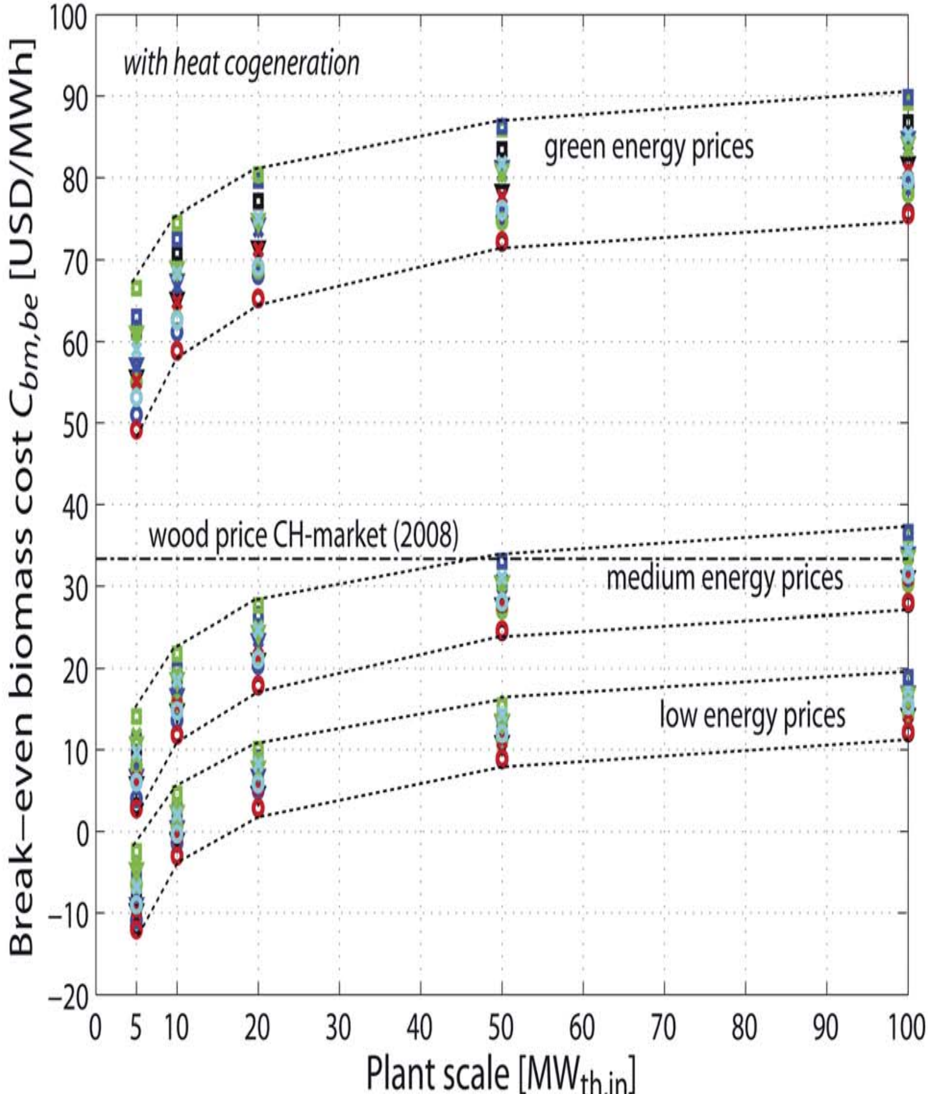
- Resource productivity : + 33% per forest m²



From conventional (58%) to optimised (> 75% eff.)

Break-even cost of the resource





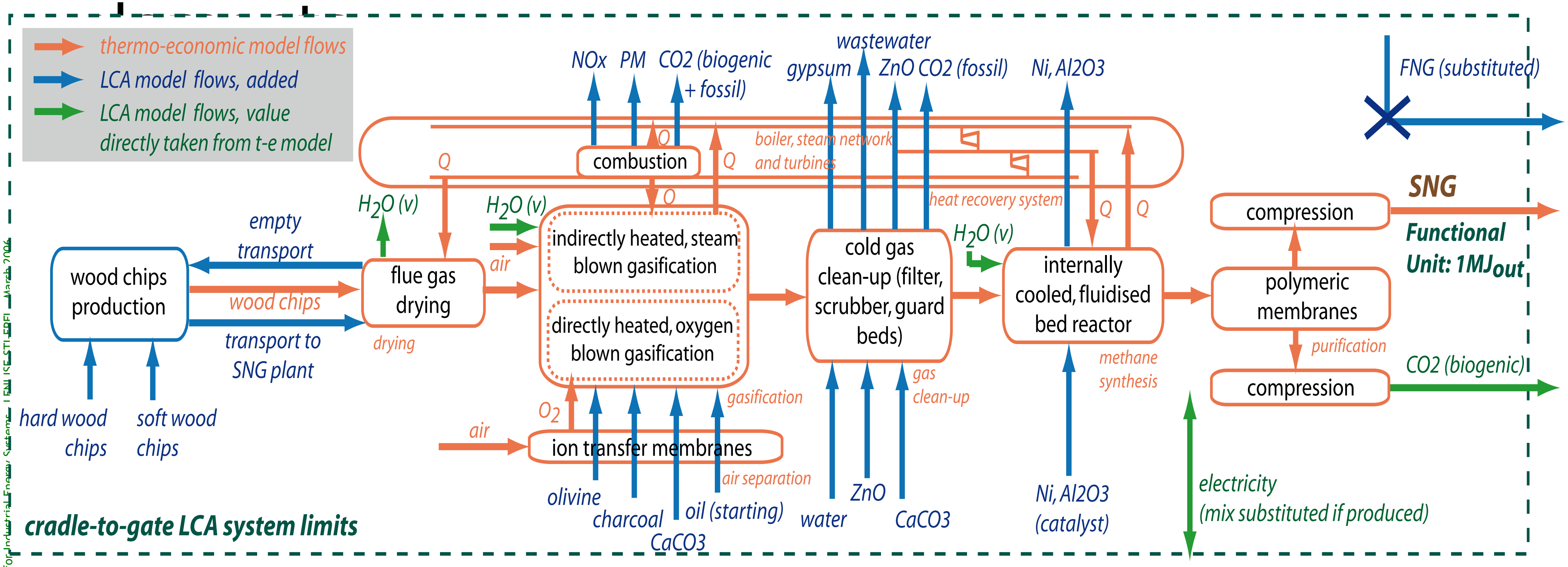
			Price scenario			CH-market[a]	
nergy vector		Unit	Green	Mid	Low	1999	2008/09
lectricity	C_{el}	\$ MWh^{-1}	180	90	60	90–135	80–160
utomotive uel & SNG	C_{SNG}	\$ MWh^{-1}	120	60	40	80–95	130–140
ndustrial heat	C_q	\$ MWh^{-1}	80	40	26.6	20–35	40–65

Including tax. Figures for 1999 are from Previdoli and Beck,[60] 2008/09 ; approximate.

Environmental Process performance indicators

Identification of Life Cycle Inventory elements

- Process superstructure, extended with LCI

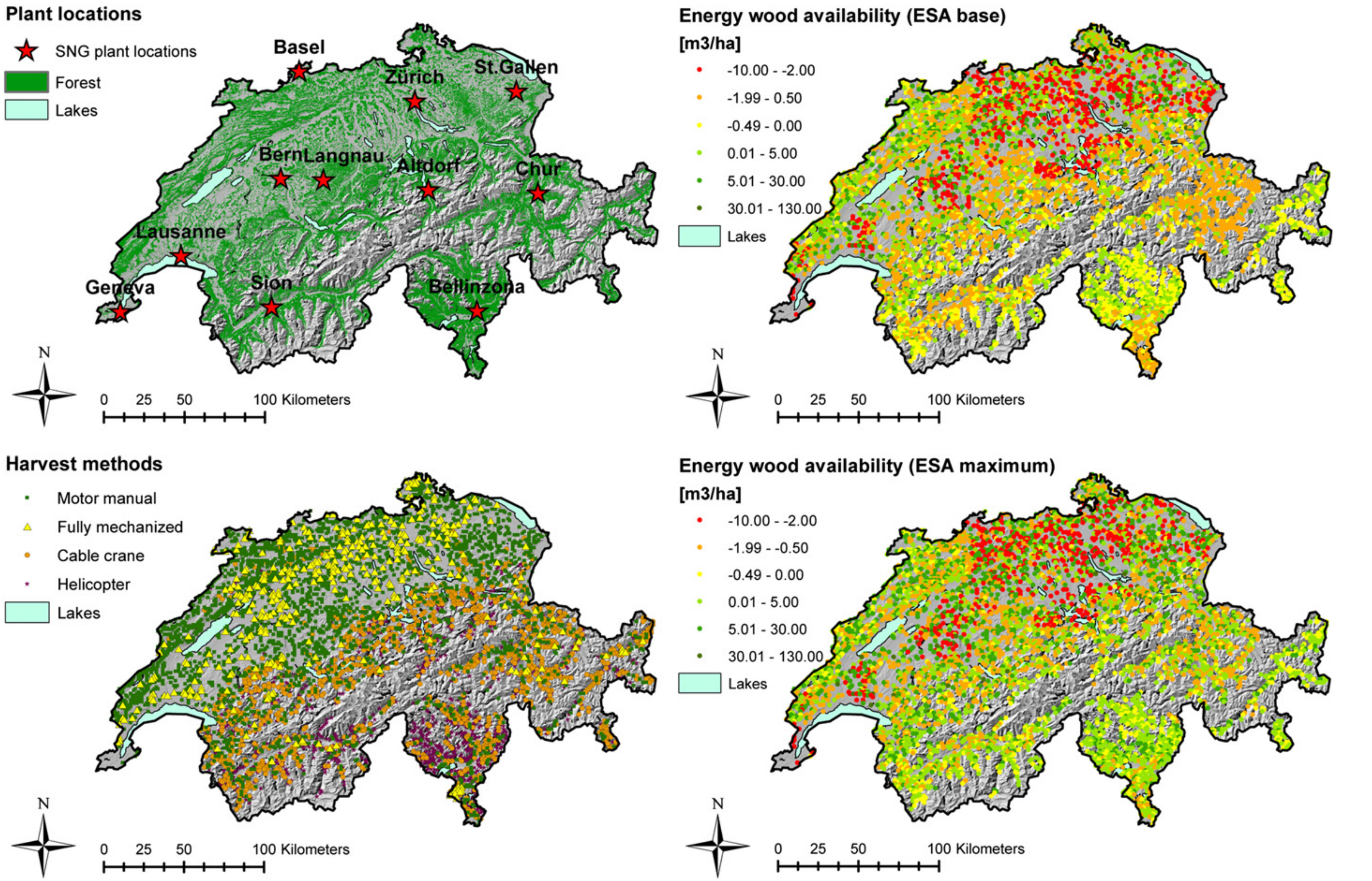


➡use of ecoinvent emission database (1) for each LCI element, to take into account off-site emissions

(1) http://www.ecoinvent.org

Gerber, L., Gassner, M., and Maréchal, F. (2009). Integration of LCA in a thermo-economic model for multi-objective process optimization of SNG production from woody biomass, , (), 1405-1410

Biomass availability



Steubing B, et al., Identifying environmentally and economically optimal bioenergy plant sizes and locations: A spatial model of wood-based SNG value chains, Renewable Energy (2012), http://dx.doi.org/10.1016/j.renene.2012.08.018

Transportation costs

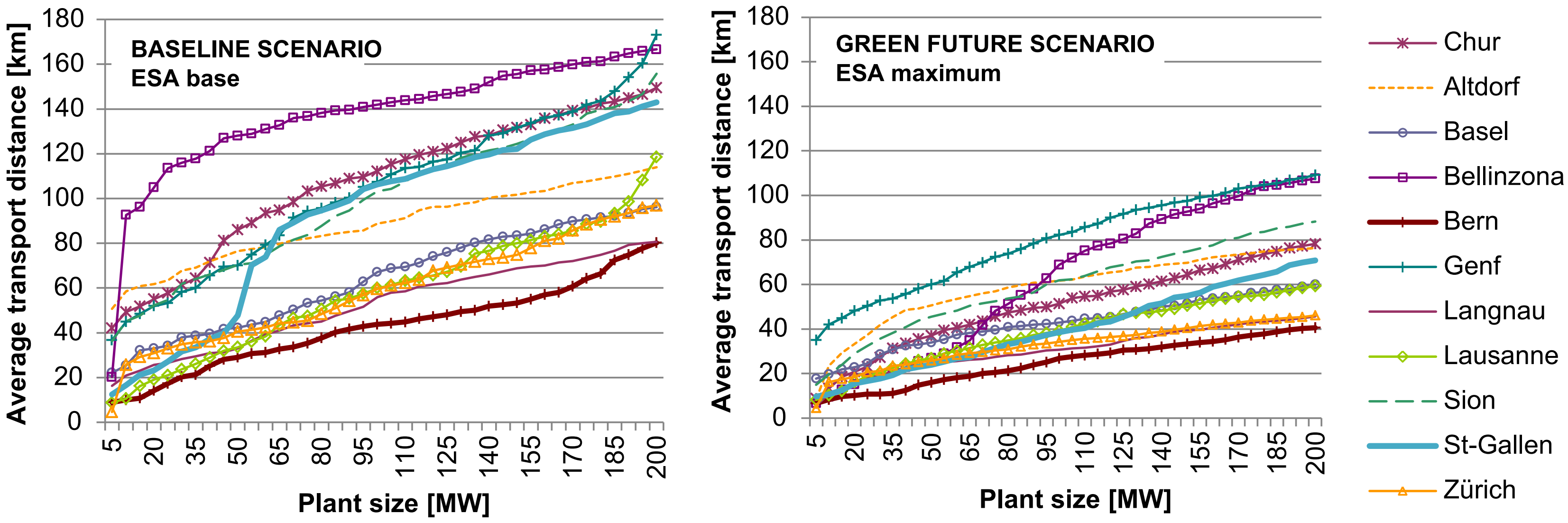
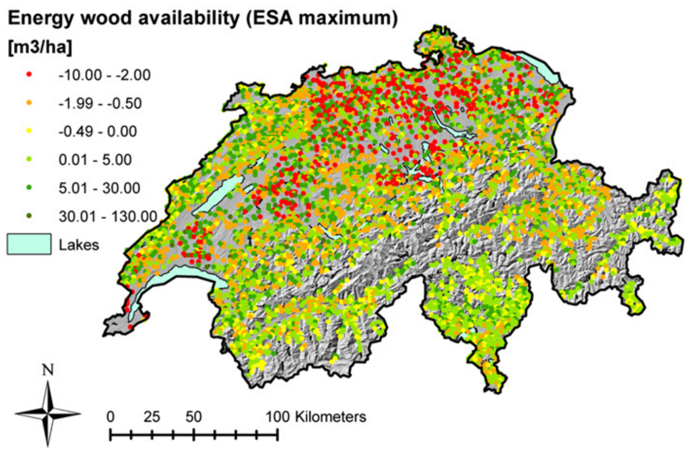


Fig. 6. Transport distances according to plant sizes, locations, and wood availability scenario (left: ESA base, right: ESA maximum).

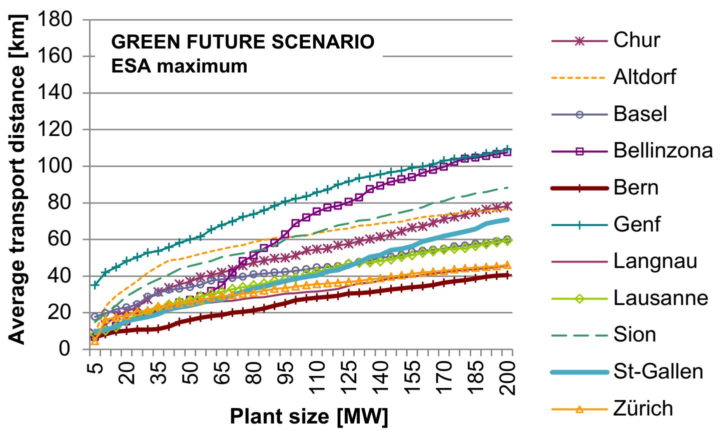
Steubing B, et al., Identifying environmentally and economically optimal bioenergy plant sizes and locations: A spatial model of wood-based SNG value chains, Renewable Energy (2012), http://dx.doi.org/10.1016/j.renene.2012.08.018

Plant location

Area = 40 km2



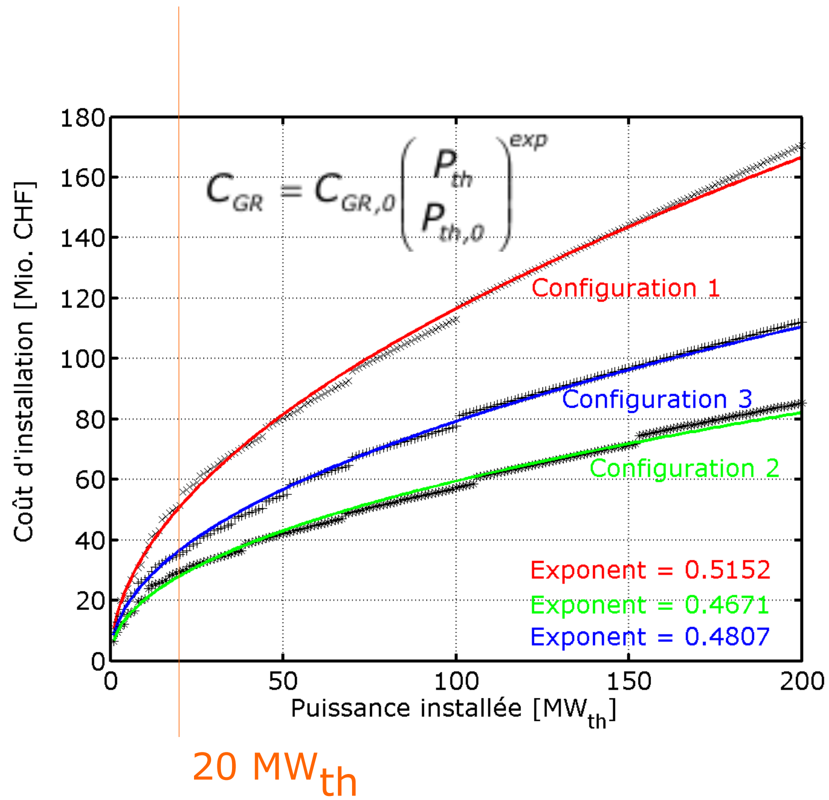
Transport = 10 % of the energy



Process Size => Investment

20 MW_{th}:

- 51.4 Mio. CHF (1)
- 29.5 Mio. CHF (2)
- 35.4 Mio. CHF (3)

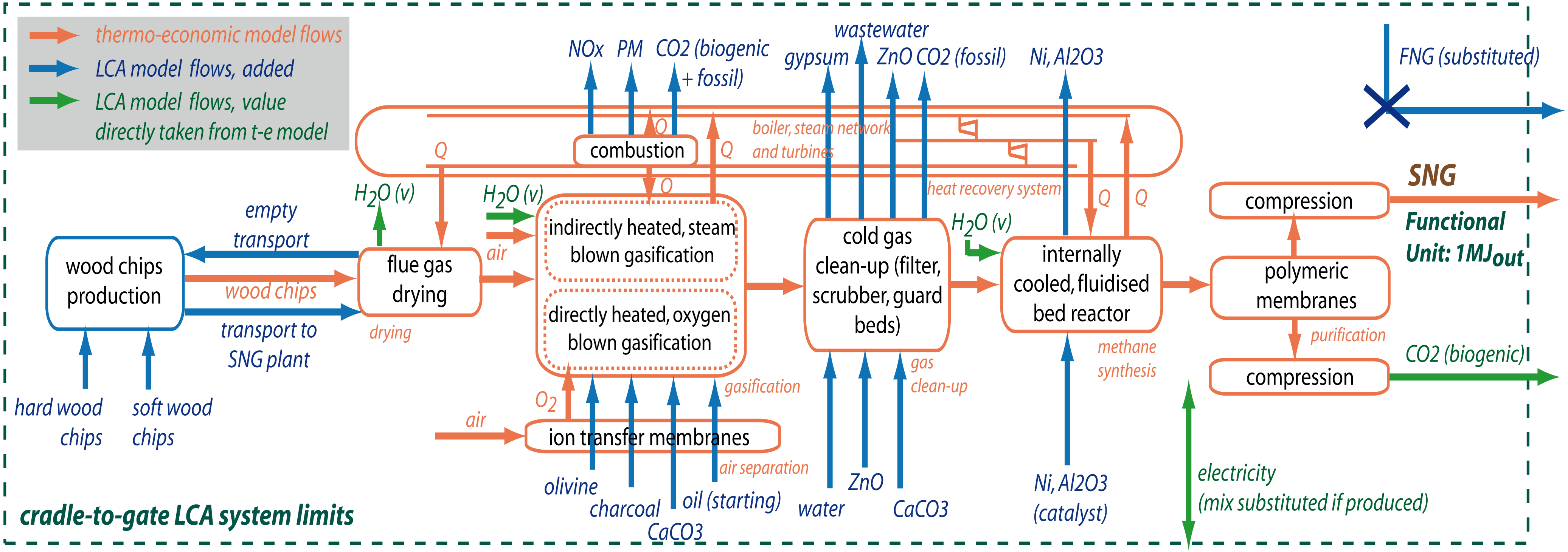


Efficiency : 5000 Wyear/year/ha

Environmental Process performance indicators

Identification of Life Cycle Inventory elements

- **Process superstructure, extended with LCI**



➡ **use of ecoinvent emission database (1) for each LCI element, to take into account off-site emissions**

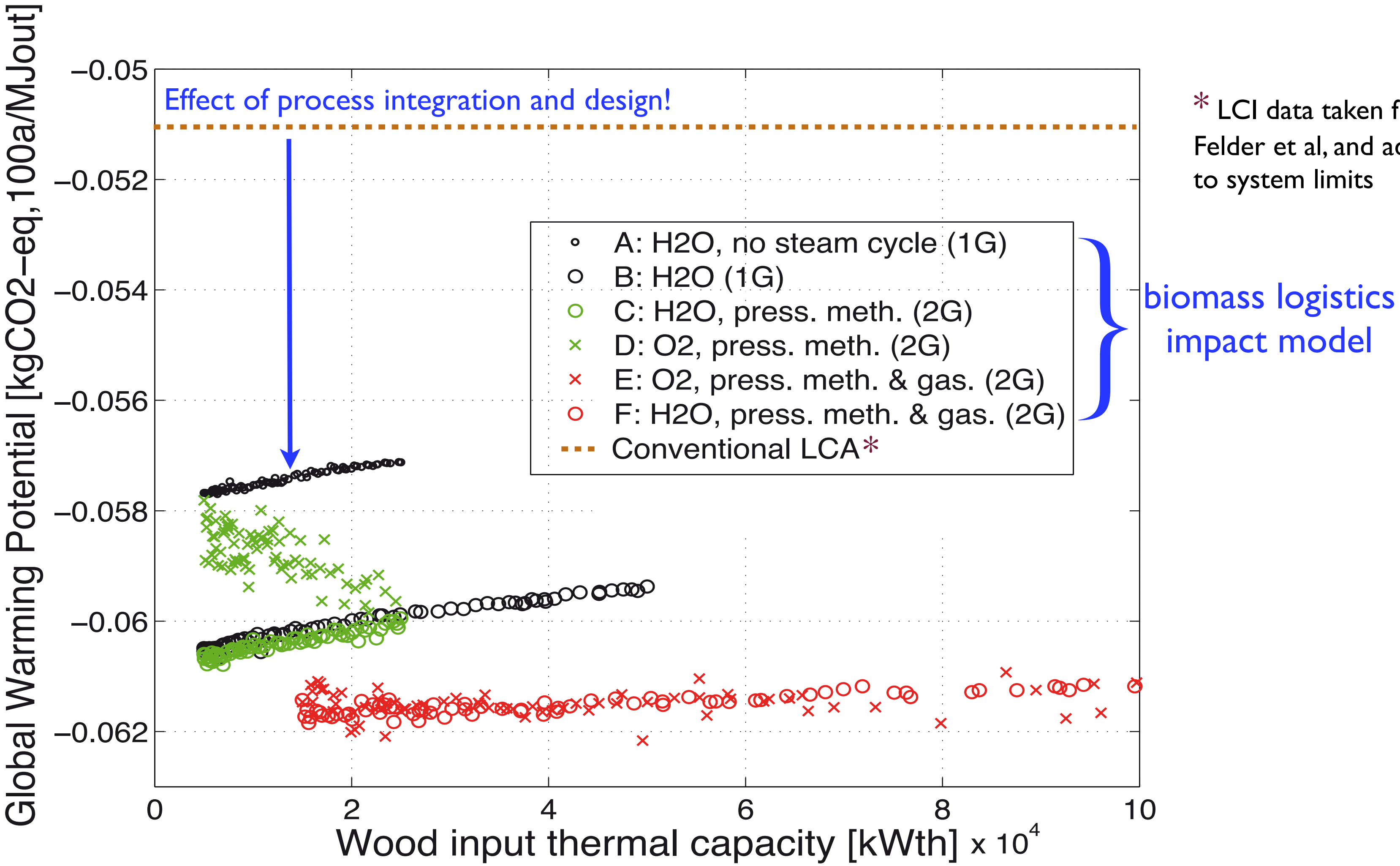
(1) http://www.ecoinvent.org

Gerber, L. et al., 2010 Comp & Chem Eng., 1405-1410

Integration of LCIA in the methodology

Perspective: plant scale-up vs. biomass logistics

The biomass Logistics has an influence on the plant impact

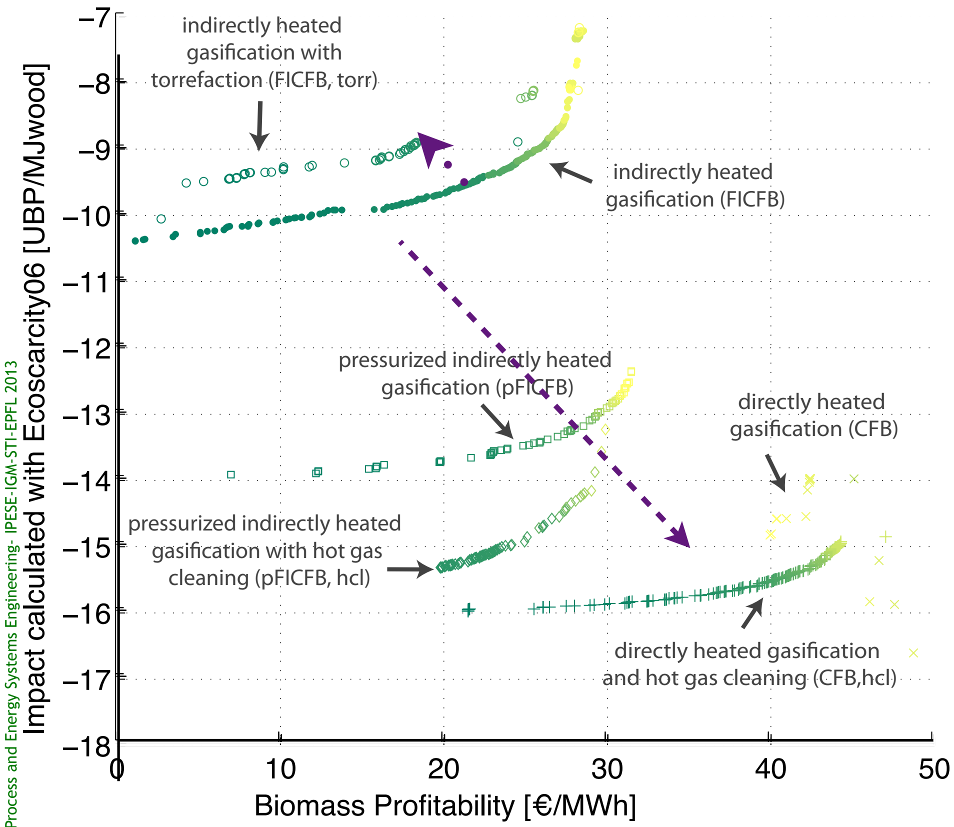


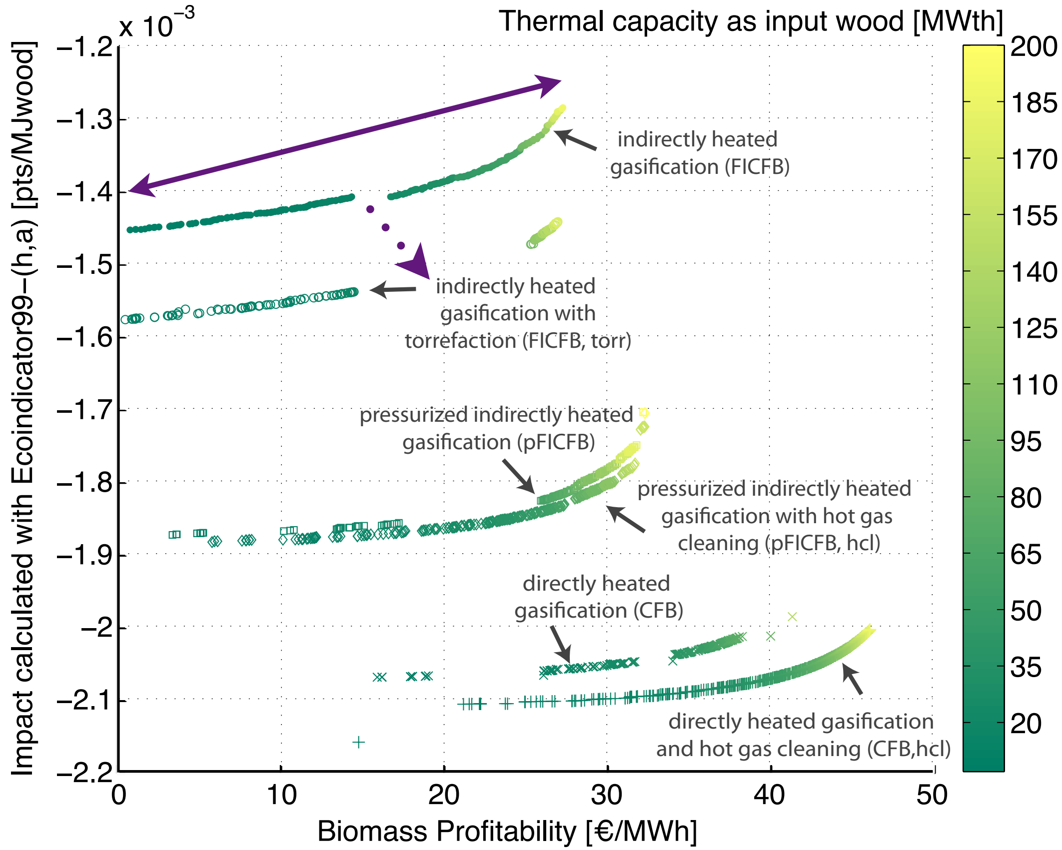
* LCI data taken from Felder et al, and adapted to system limits

→ *Optimal plant size with respect to biomass logistics*

Multi-objective optimization results

- Optimal configurations

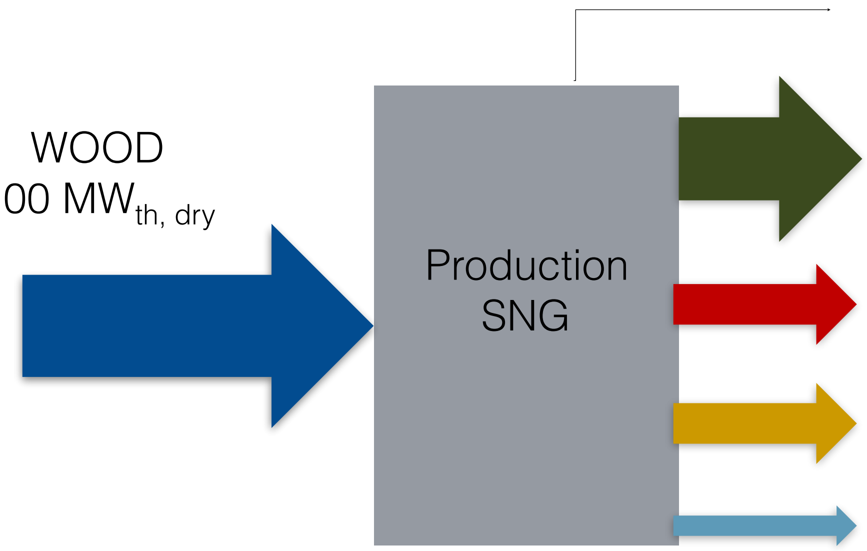




1. *Process scale*
2. *Technology evolution*
3. *Environmental objective function*

Thesis L. Gerber 2012

The green boiler => use of the renewable resource



- **Co production of biofuel from wood**
  - **Synthetic natural gas, methanol, DME, F-T fuels**
  - **CO2 capture**
  - **Exothermic => Heat supply**
  - **Cogeneration of Heat**

COST OF HEAT

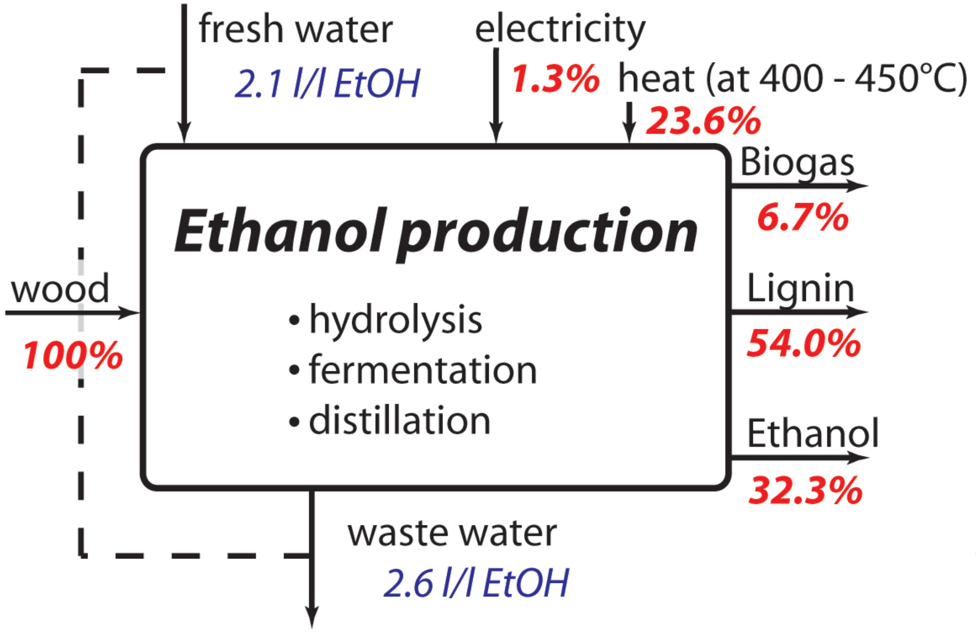
25 $/MWh (- 47 $/MWh)*

** with CO2 tax*

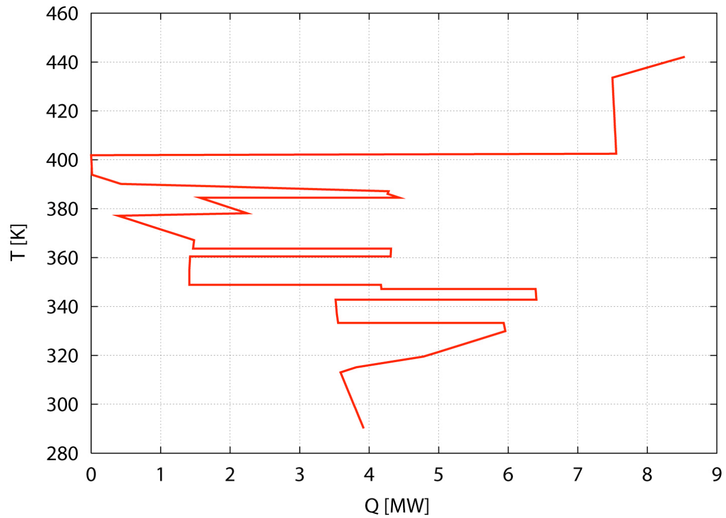
With market price of WOOD (40$/MWh) and NG (65 $/MWh) and with CO2 taxes (80 CHF/ton), also for capture
8000 hours/year of operation

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:



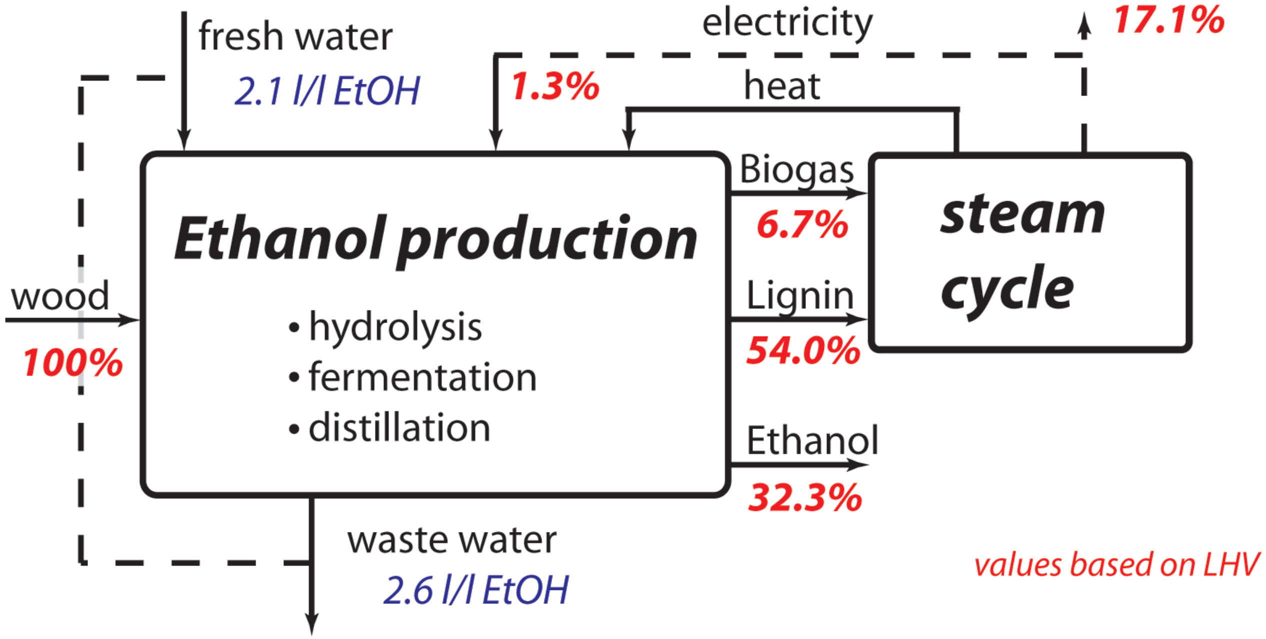
values based on LHV

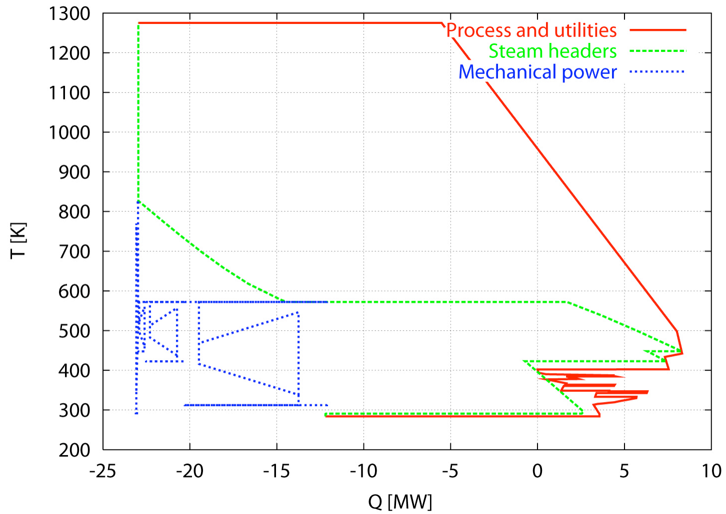


input: $58\ MW_{th,wood}$

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





input: $58\ MW_{th,wood}$

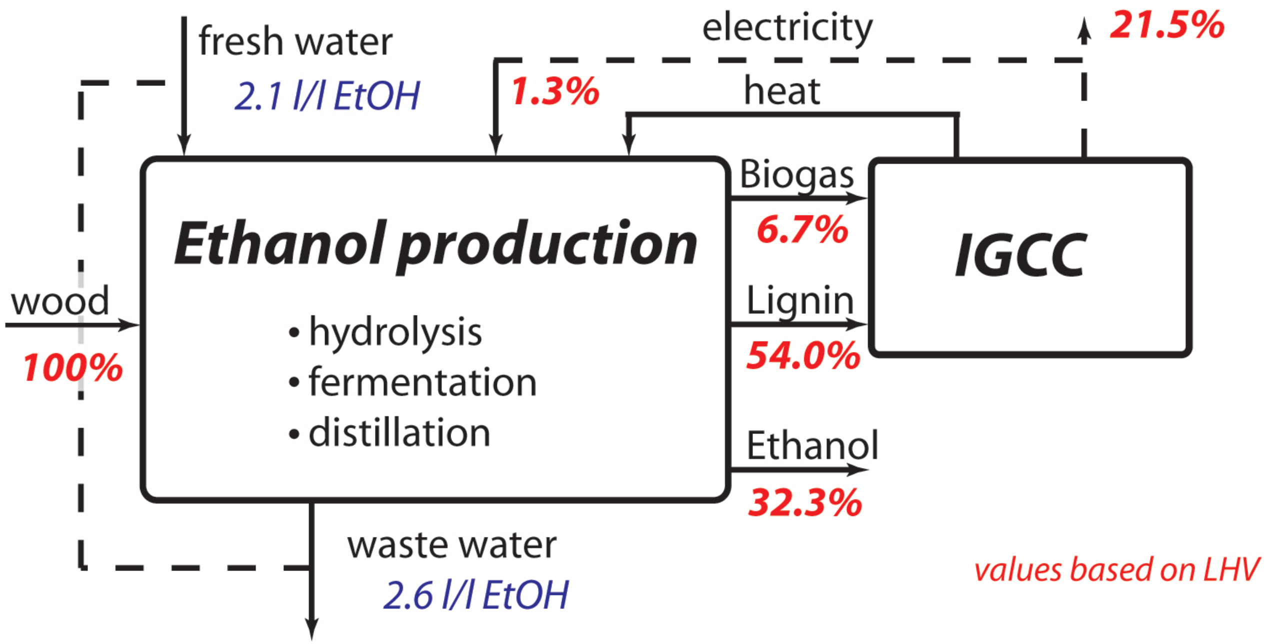
		steam cycle
Input	wood	100 %
Output	ethanol	32.3 %
	SNG	-
	electricity	17.1 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %
total efficiency		49.4 %

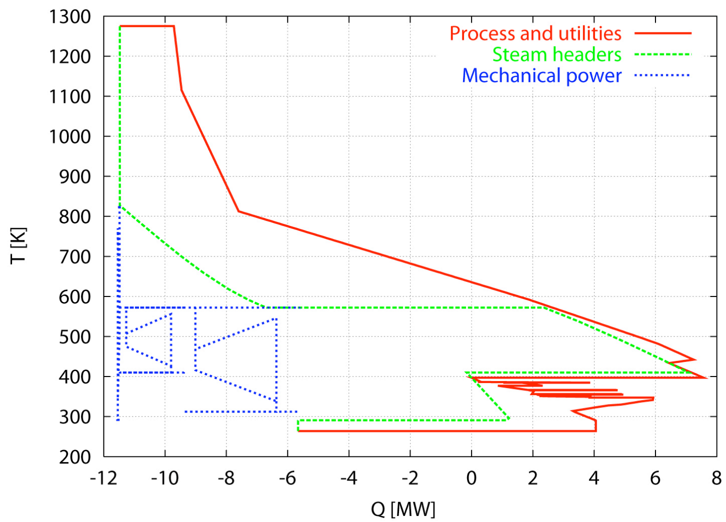
Energy balance for different process integration options (without seed train, non-optimised).

Site integration: process couplings

EtOH & SNG

Ethanol production from lignocellulosic biomass:





input: $58\ MW_{th,wood}$

		steam cycle	IGCC
Input	wood	100 %	100 %
Output	ethanol	32.3 %	32.3 %
	SNG	-	-
	electricity	17.1 %	21.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %
total efficiency		49.4 %	53.8 %

Energy balance for different process integration options (without seed train, non-optimised).

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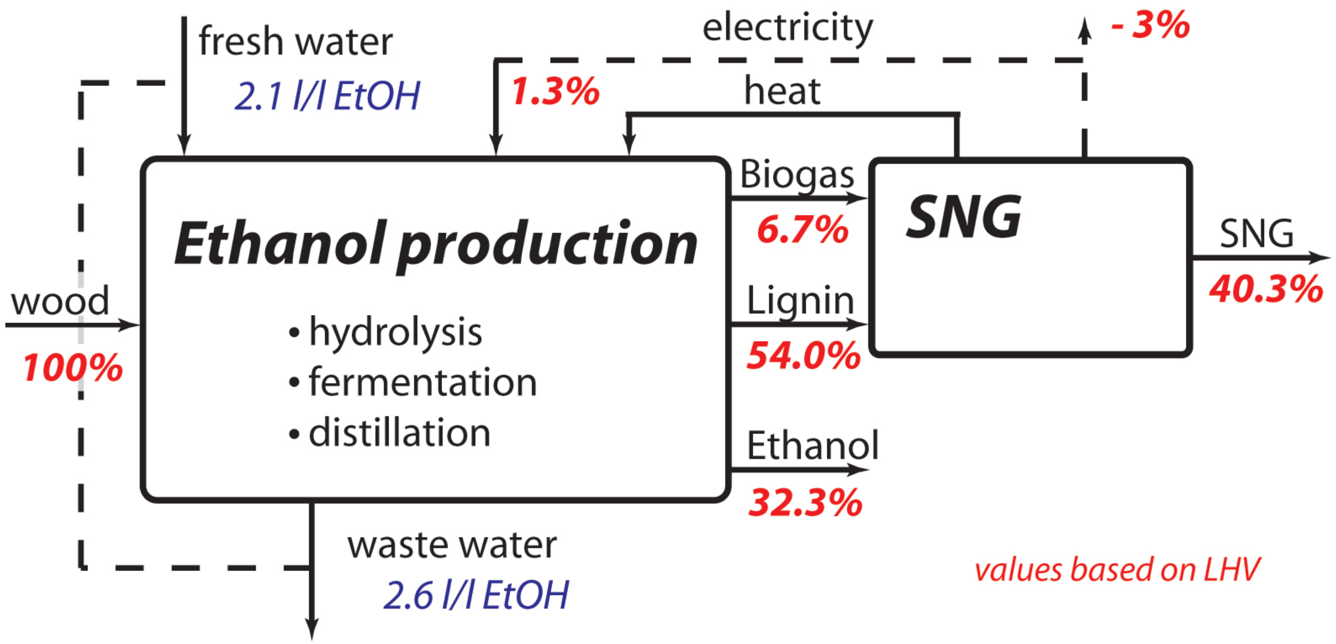
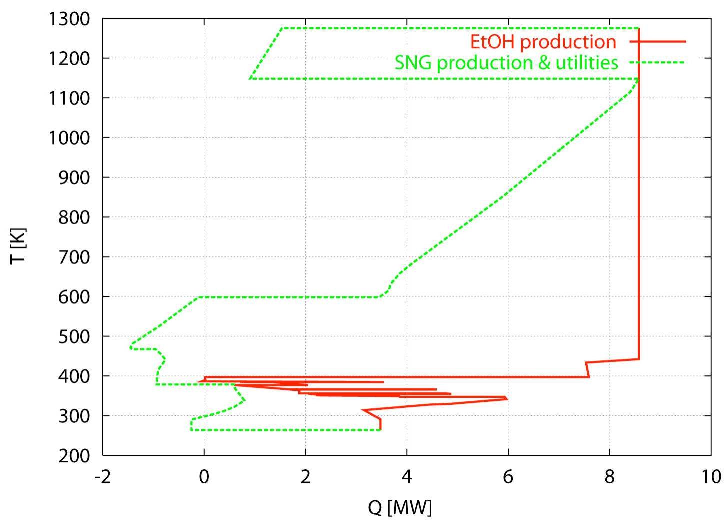
Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





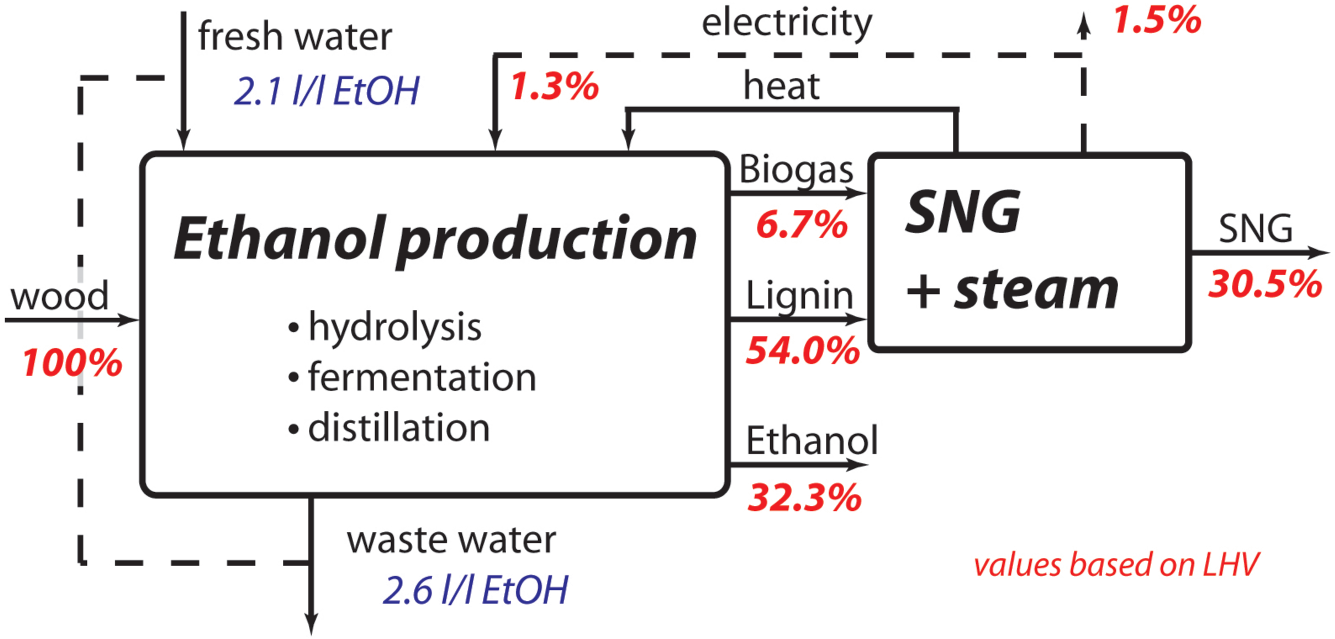
input: $58\ MW_{th,wood}$

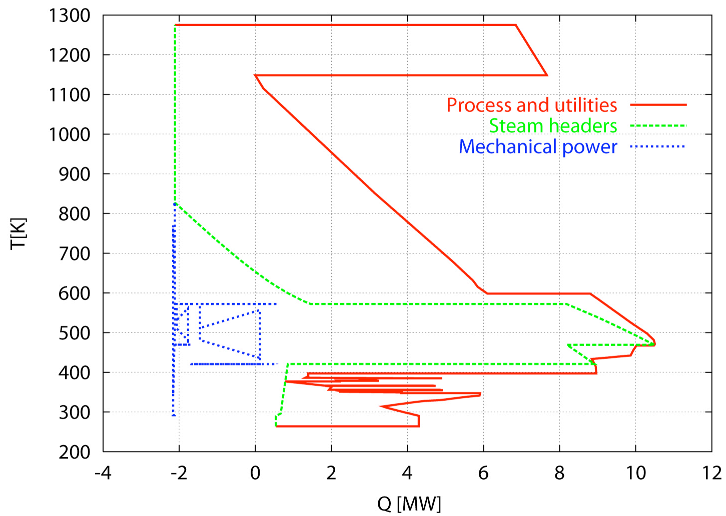
		steam cycle	IGCC	SNG
Input	wood	100 %	100 %	100 %
Output	ethanol	32.3 %	32.3 %	32.3 %
	SNG	-	-	40.3 %
	electricity	17.1 %	21.5 %	-3.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %
total efficiency		49.4 %	53.8 %	70.5 %

Energy balance for different process integration options (without seed train, non-optimised).

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Ethanol production from lignocellulosic biomass:



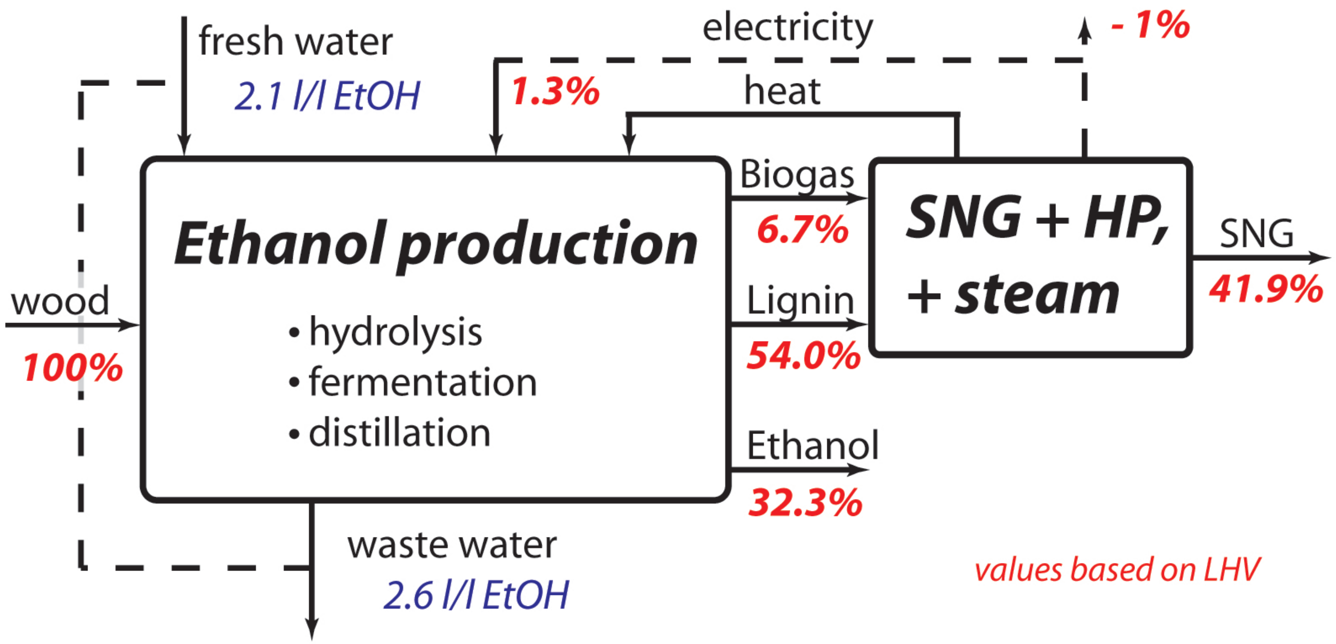


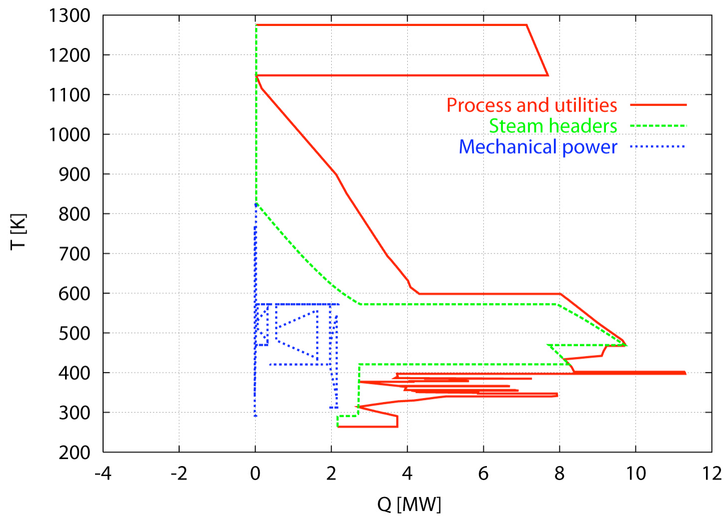
input: $58\ MW_{th,wood}$

		steam cycle	IGCC	SNG	+ steam
Input	wood	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %
Output	SNG	-	-	40.3 %	30.5 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %

Energy balance for different process integration options (without seed train, non-optimised).

Ethanol production from lignocellulosic biomass:





input: 58 $MW_{th,wood}$

		steam cycle	IGCC	SNG	+ steam	+ HP
Input	wood	100 %	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %	32.2 %
Output	SNG	-	-	40.3 %	30.5 %	41.9 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %	-1.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %	72.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %	73.1 %

Energy balance for different process integration options (without seed train, non-optimised).

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

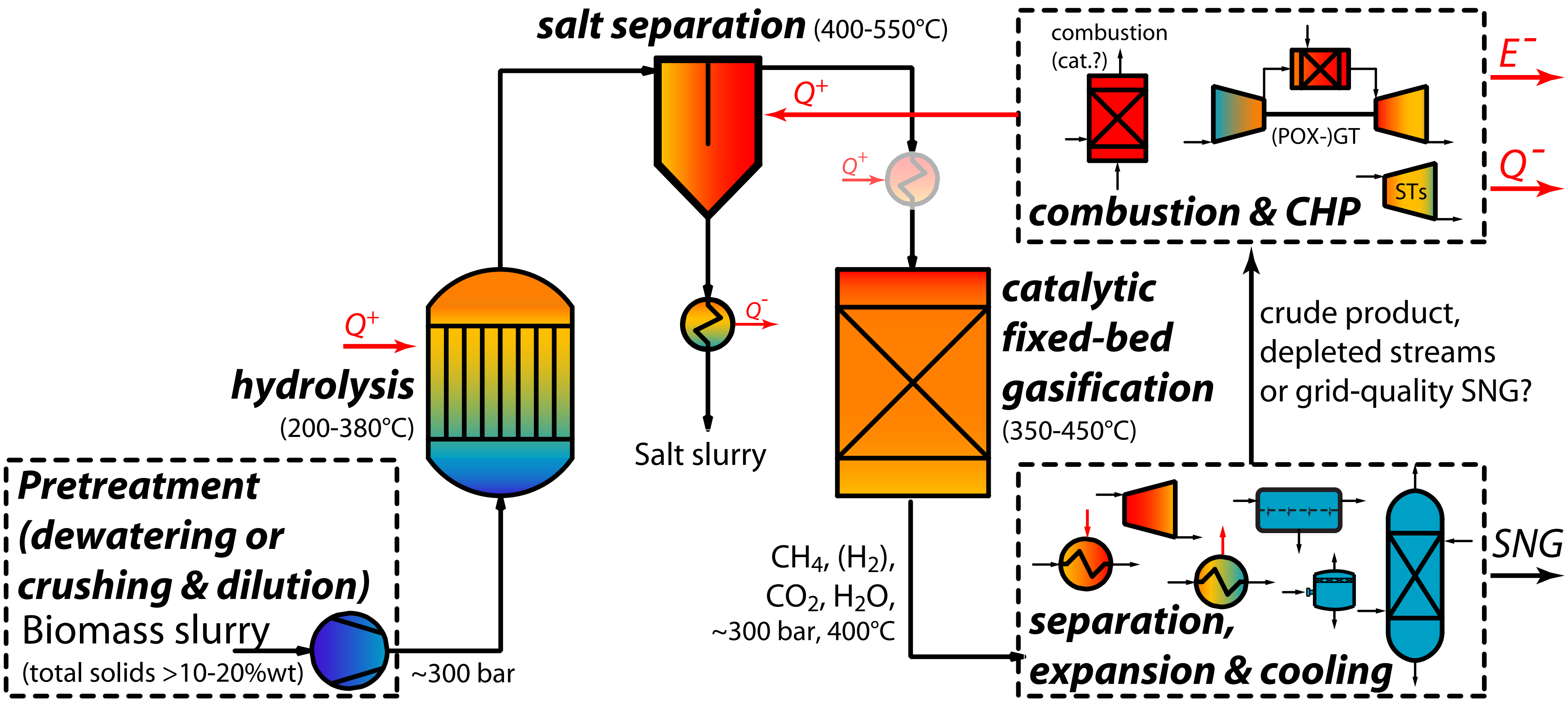
6. Overall System analysis

competing technologies

6. Overall System analysis

other feedstocks (waste biomass)

Hydrothermal supercritical gasification

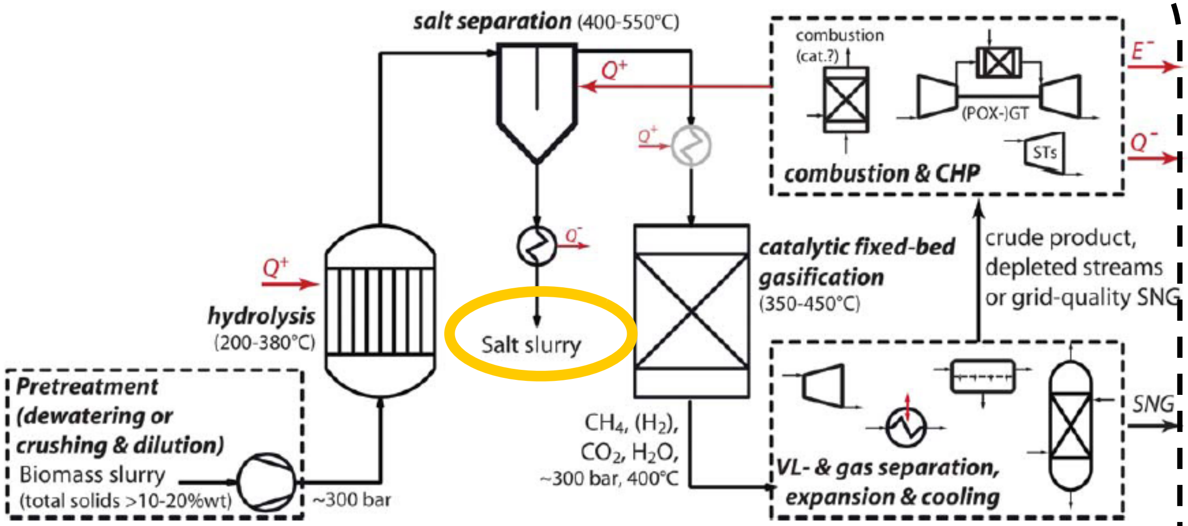


Martin Gassner, Frederic Vogel, Georges Heyen and Francois Marechal , *Process design of SNG production by hydrothermal gasification of waste biomass: Thermo-economic process modelling and integration*, submitted to Energy & Environmental Science (2010)

New technology Hydrothermal gasification

15% solids content in feedstock – 94% CH_4 in crude SNG
Sludge treatment

INPUT:
10 MW$_{dry}$
15 % solid content



Conceptual process flow diagram for hydrothermal gasification in supercritical water.

SNG 6.2 MW

ELEC 0.25 MWe

Salts

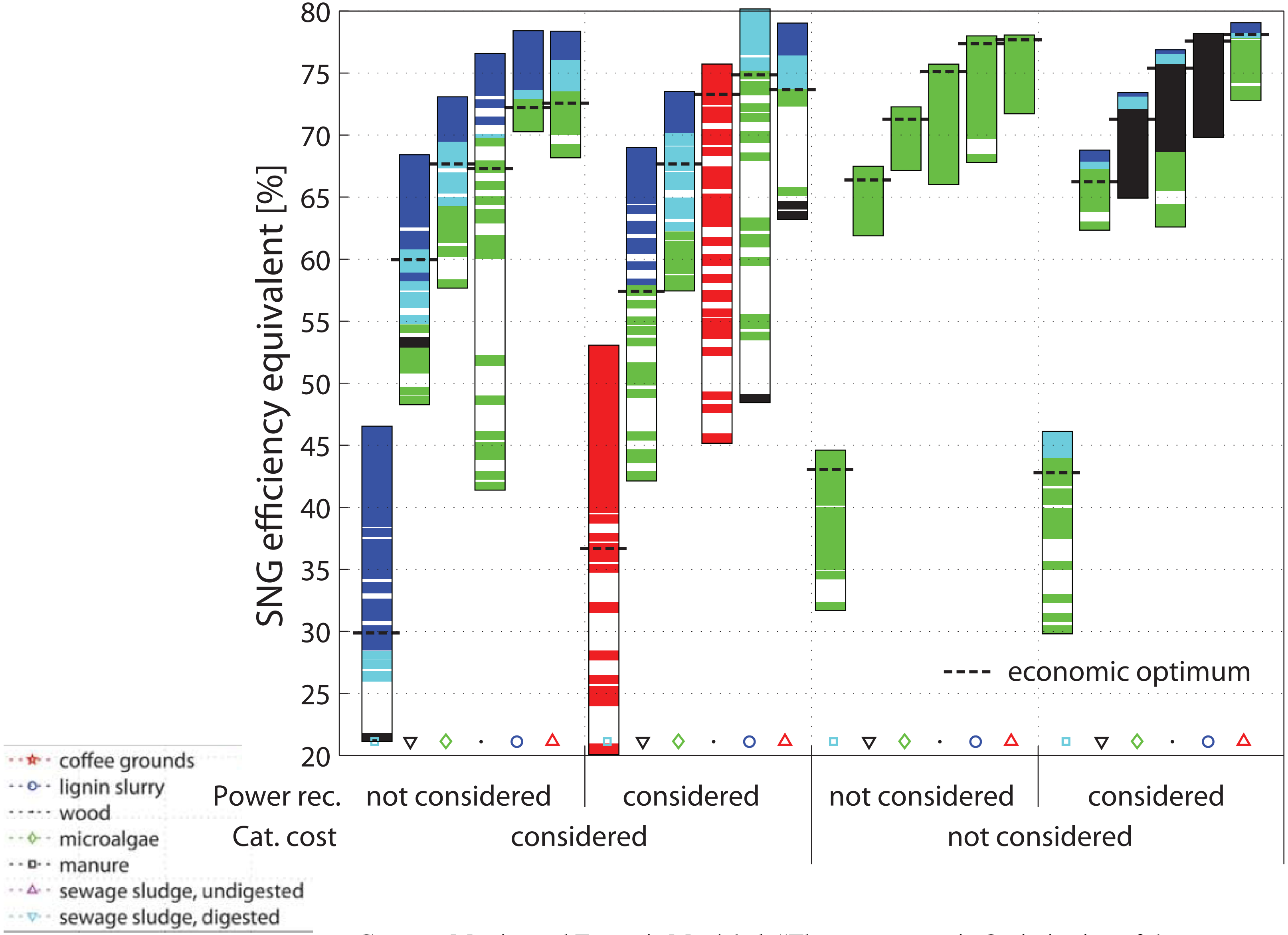
CO2

Water

- Depleted gas are not sufficient to close the energy balance;
- Considering a 94%vol methane rich crude product, about 8 % of the total massflow has to be burned in order to satisfy the energy demand of the process ;

Gassner, Martin, and François Maréchal. "Thermo-economic Optimisation of the Polygeneration of Synthetic Natural Gas (SNG), Power and Heat from Lignocellulosic Biomass by Gasification and Methanation." *Energy and Environmental Science* 5, no. 2 (2012): 5768 – 5789.

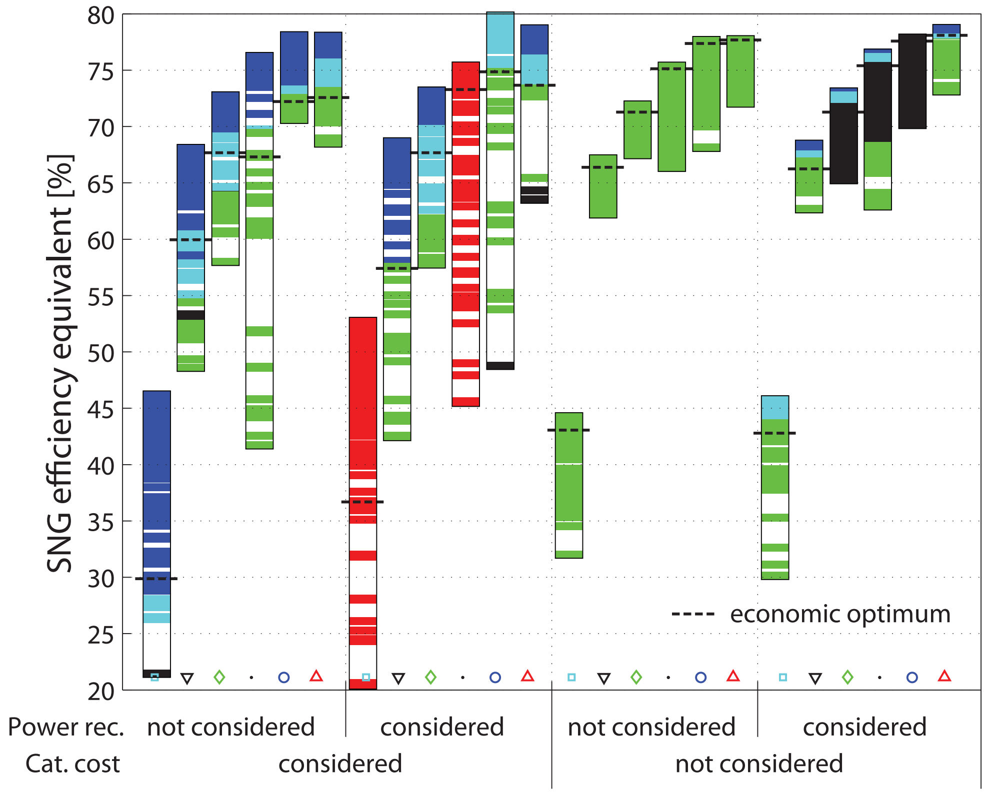
Results for different wet biomass substrates

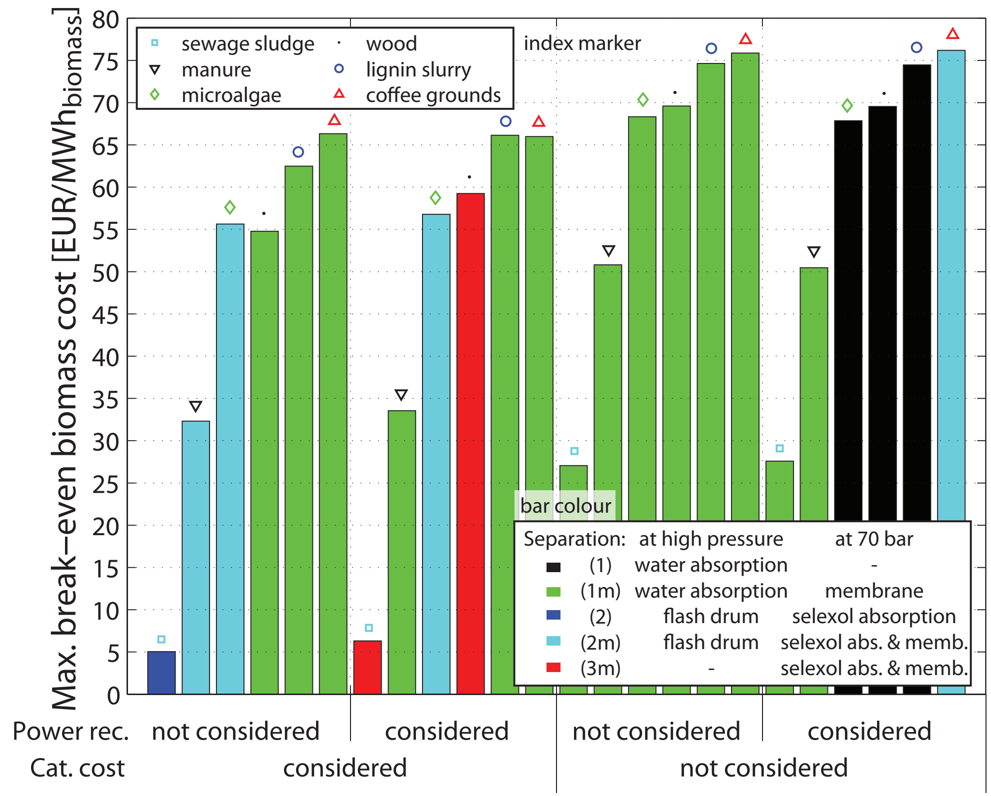


Gassner, Martin, and François Maréchal. "Thermo-economic Optimisation of the Polygeneration of Synthetic Natural Gas (SNG), Power and Heat from Lignocellulosic Biomass by Gasification and Methanation." *Energy and Environmental Science* 5, no. 2 (2012): 5768 – 5789.

Process optimisation
(2) Thermo-economic performance for different substrates

Optimal plant configurations





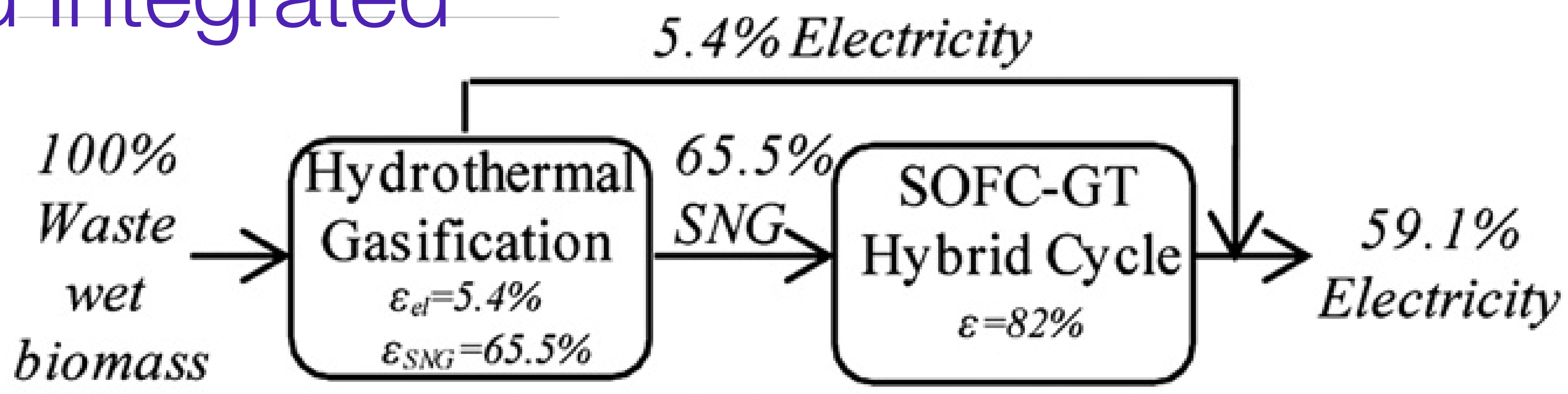
evolution on Pareto front

most economic conf. at 20 MW$_{th}$

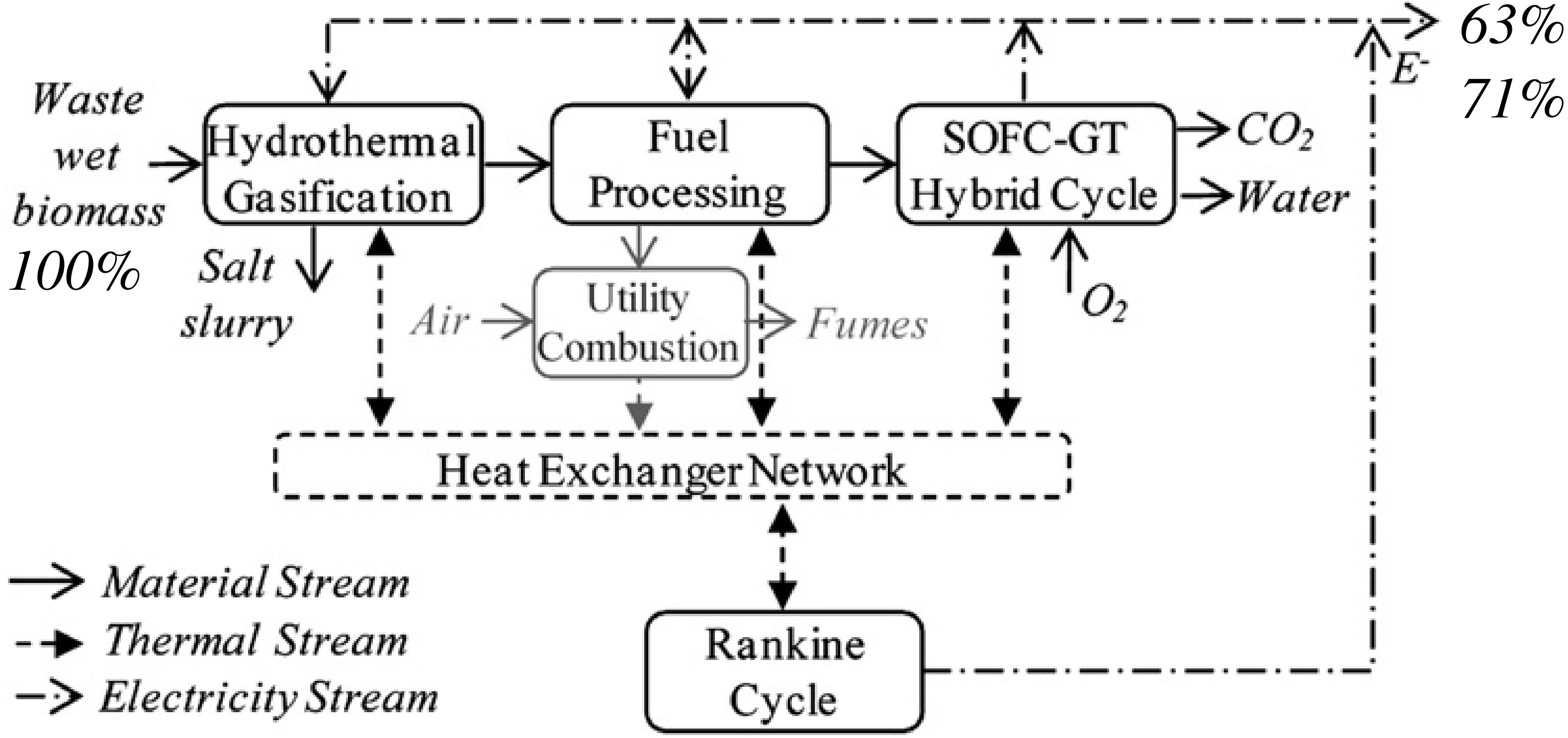
Martin Gassner, Frederic Vogel, Georges Heyen and Francois Marechal, *Process design of SNG production by hydrothermal gasification of waste biomass: Process optimisation for selected substrates*, Energy & Environmental Science (2010)

Integrate or not ?

Grid Integrated



Integrated



Facchinetti, E. et al. *Energy* 41, no. 1 (May 2012): 408–419.

Use of Natural Gas to provide energy services

Cogénération

Technologie	Rendements [% du PCI] électrique	chaleur	Remarques/Source
Chaudière à condensation	0	106	Hoval AG
	0	102	Ø, Ecoinvent
Moteur à gaz	34	52	Ø CH, OFEN (2003)
	42	40	potentiel max. (données int.)
Turbine à gaz	28	48	Ø CH, OFEN (2003)
	30	50	potentiel max. (données int.)
Cycle combiné	35	45	petite centrale à cogénération
	57	0	centrale industrielle sans cogén.
SOFC	45	40	très petite échelle, (labo/démo)
	60	25	potentiel max., (labo)
	80	20	SOFC-GT

Utilisation comme carburant (tank-wheel)

	km/MJ			l/100 km[a]			g_{CO2}/km[b]		
Carburant	2002[c]	2010[d]	2005[e]	2002[c]	2010[d]	2005[e]	2002[c]	2010[d]	2005[e]
gaz naturel comp.	0.436	0.667	0.325	7.20	4.70	9.65	135	80	
essence	0.475	0.625	0.362	6.60	5.02	8.66	160	120	205
diesel	0.556	0.667	0.402	5.00	4.17	6.92	140	110	184
électrique		2.18			1.44		0	0	

[a] Pour gaz naturel et électrique, l'equivalence essence est donnée.

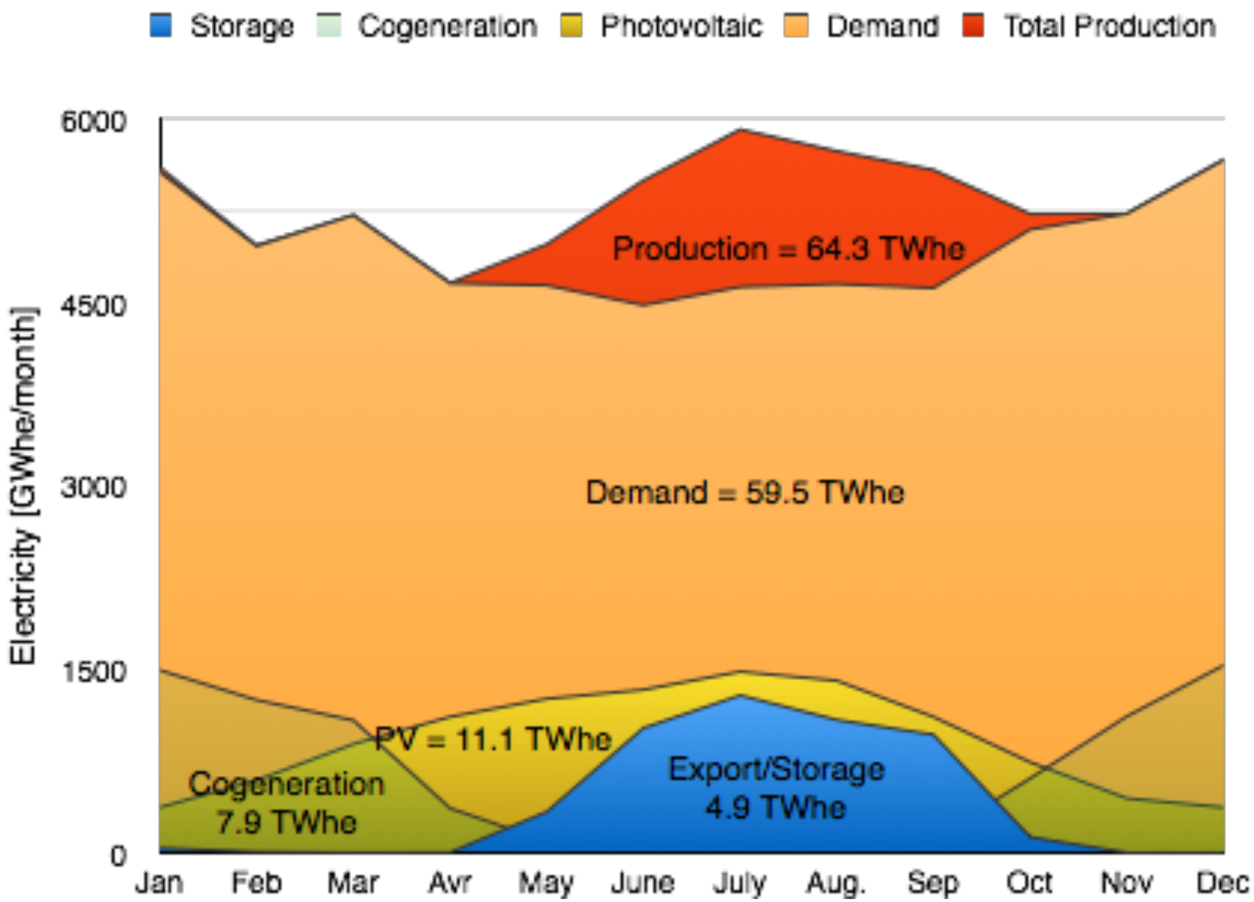
[b] sans chaine de production du carburant et correction en equivalents CO_2

[c] Nouvelles voitures, essence : *direct injection spark ignition*, diesel : *direct injection compression ignition*, gaz : *port injection spark ignition, CNG*.

[d] comme [b], mais moteur hybride

[e] moyenne du parc de voitures Suisse selon ecoinvent

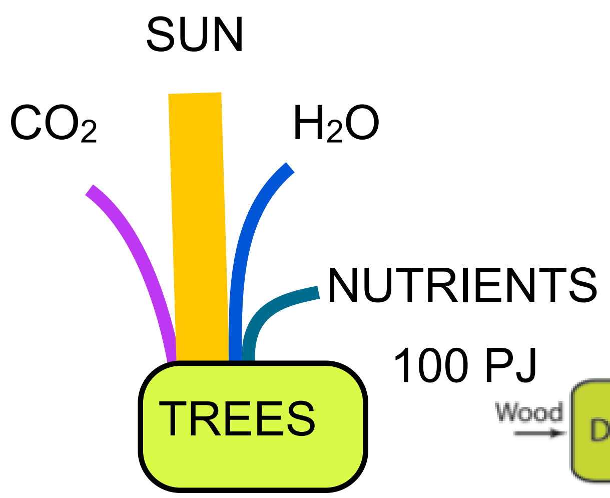
- Who is going to use the extra amount in the Summer ?
- Note : seasonal storage = 45% of PV production



http://www.energyscope.ch

Scenario 2050 : OFEN / Low

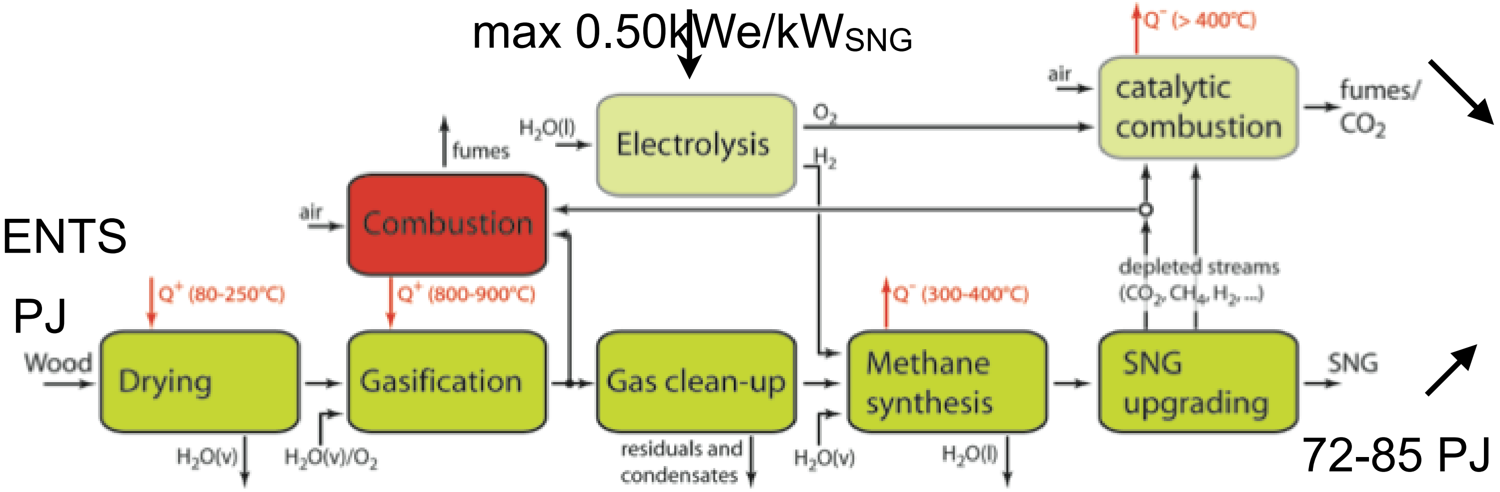
Power to gas concept



100 PJ

Carbon source

Electricity form the grid
4.7 TWhe = 13 PJ$_{SNG}$
max 0.50kWe/kW$_{SNG}$



72-85 PJ
+18%

WOOD — Natural Gas — CO2 (pure)

$$CH_{1.35}O_{0.63} + 0.3475H_2O \xrightarrow{\Delta H^0 = -10.5\ kJ/mol_{wood}} 0.51125CH_4 + 0.48875CO_2$$

$$+\ 4\ H_2 \longrightarrow +\ CH_4 \quad -\ CO_2 \quad +\ 2\ H_2O$$

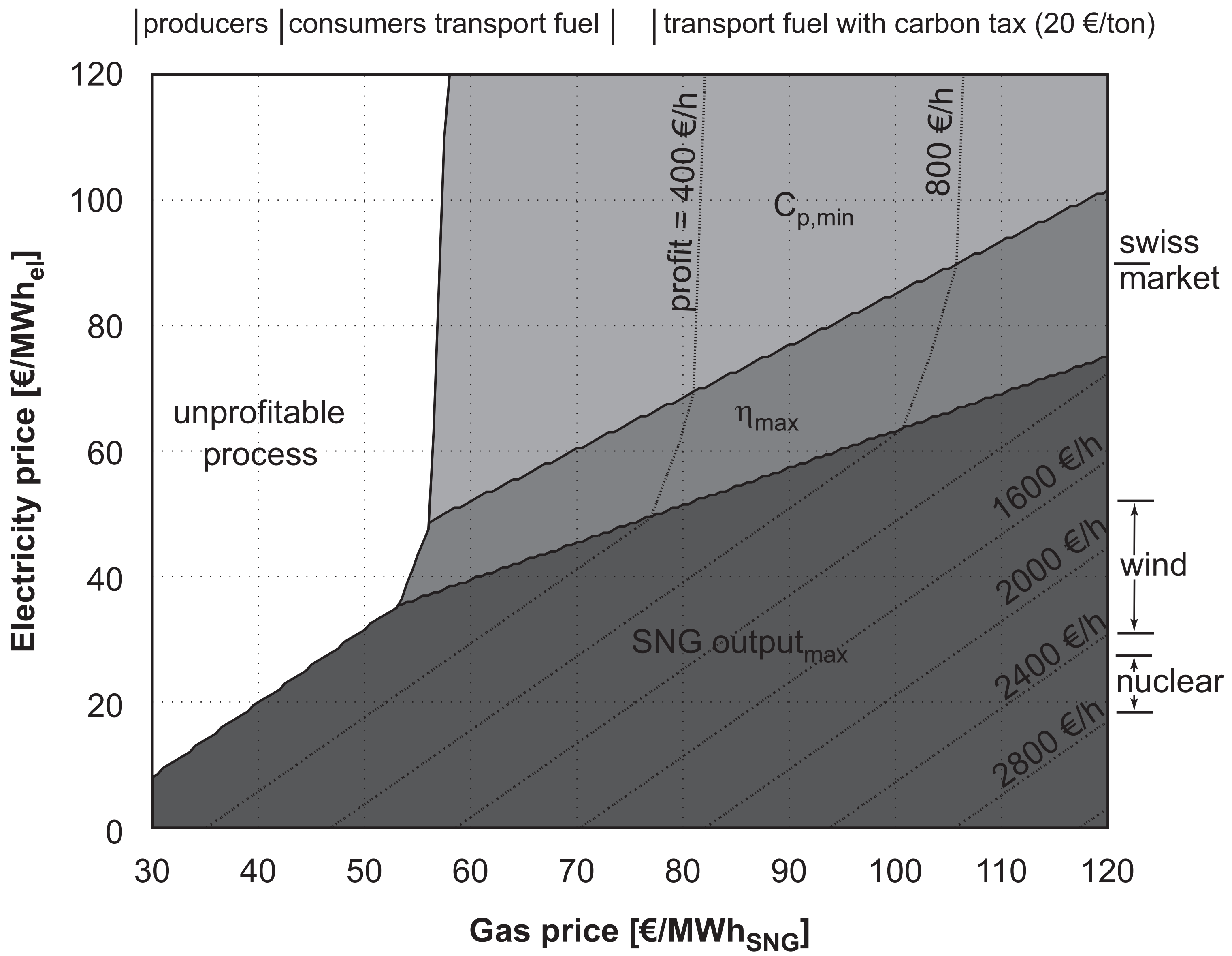
$$\Delta E^+ + 4H_2O \rightarrow +\ 4\ H_2 \quad +\ 2\ O_2$$

Storage as transportation fuel

$$\eta_c = \frac{\Delta CH4^-_{LHV}}{\Delta E^+} = 85\%$$

Gassner, M., and F. Maréchal. *Energy* 33, no. 2 (2008) 189–198.

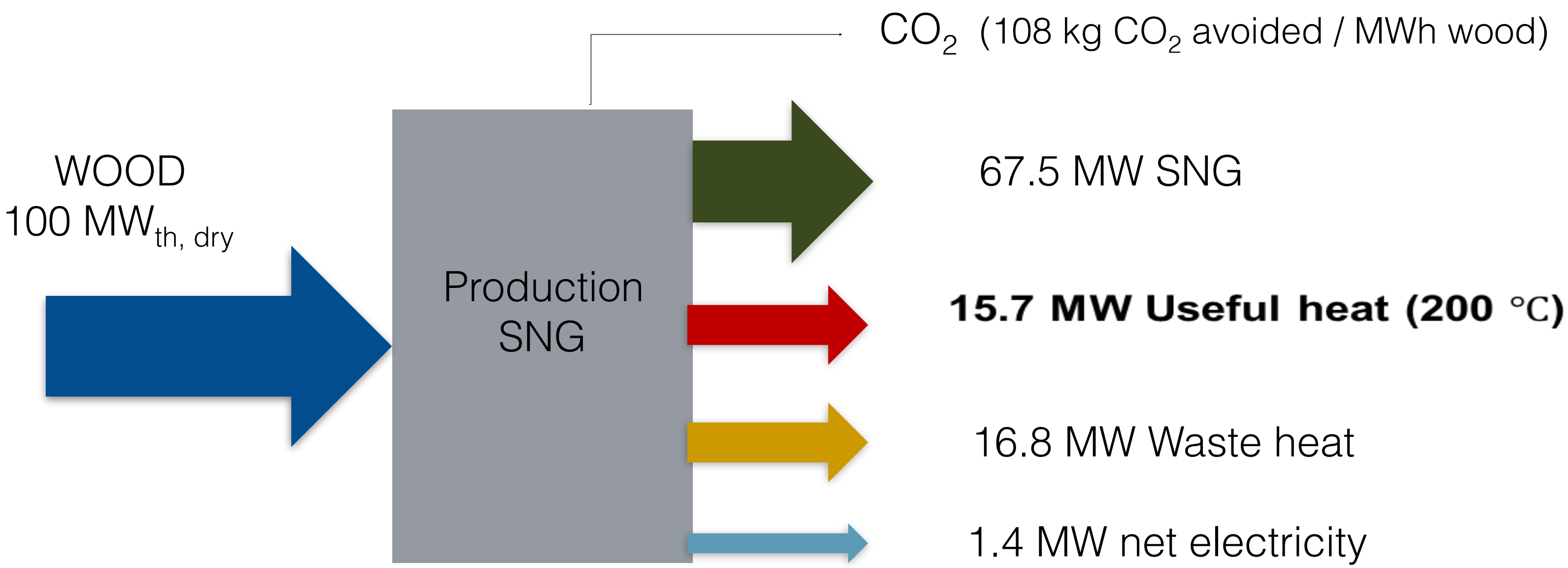
Indirectly heated gasification : electricity storage option



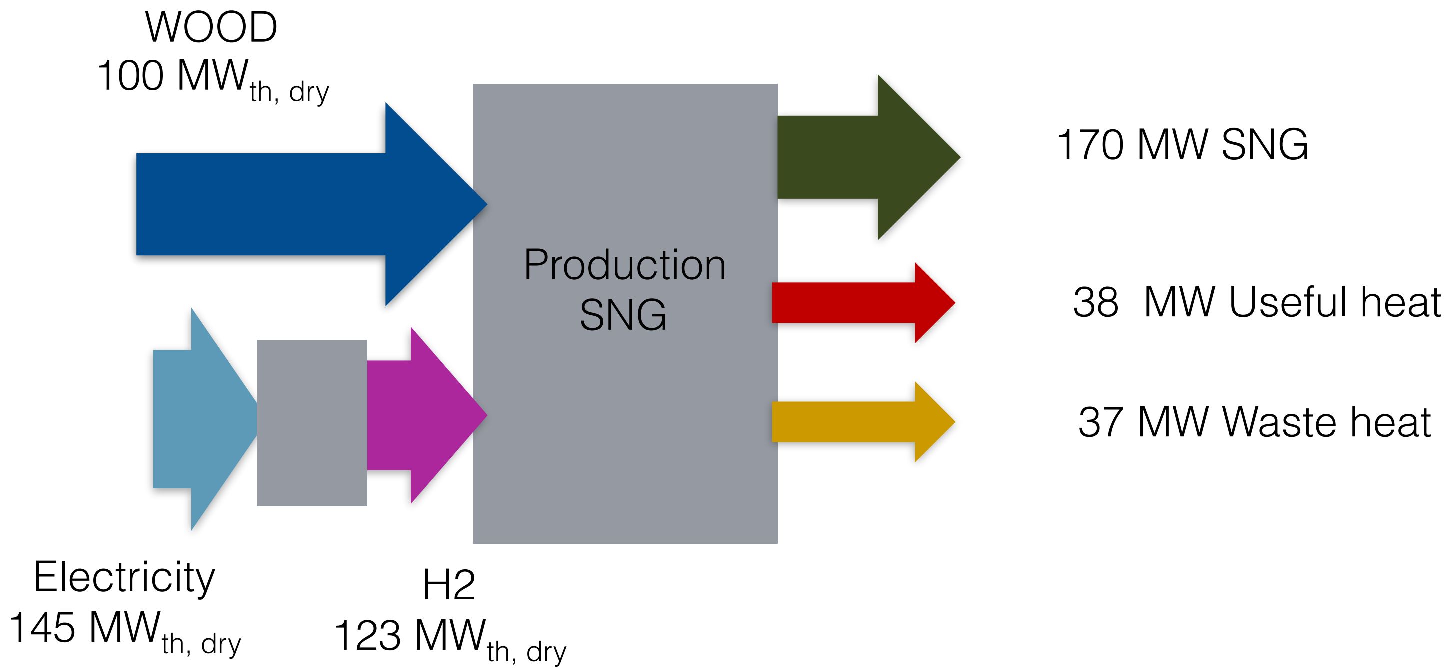
Gassner, M., and F. Maréchal. “Thermo-economic Optimisation of the Integration of Electrolysis in Synthetic Natural Gas Production from Wood.” *Energy* 33, no. 2 (February 2008): 189–198. doi:10.1016/j.energy.2007.09.010.

Green boiler and RES storage

Winter Mode



Summer Mode



Round trip efficiency of electrcity storage

- **H2 electrolysis integrated in SNG process**
  - CO2 emissions are negative (wood carbon neutral, CO2 is captured)

$$\eta_c = \frac{\Delta CH4^{-}_{LHV}}{\Delta E^{+}} = 85\%$$

- **CH4 conversion NGCC (CO2 = 0 because C biogenic)**

$$\eta_d = \frac{E^{-}}{CH4^{+}_{LHV}} = 60\%$$

- **Roundtrip efficiency**

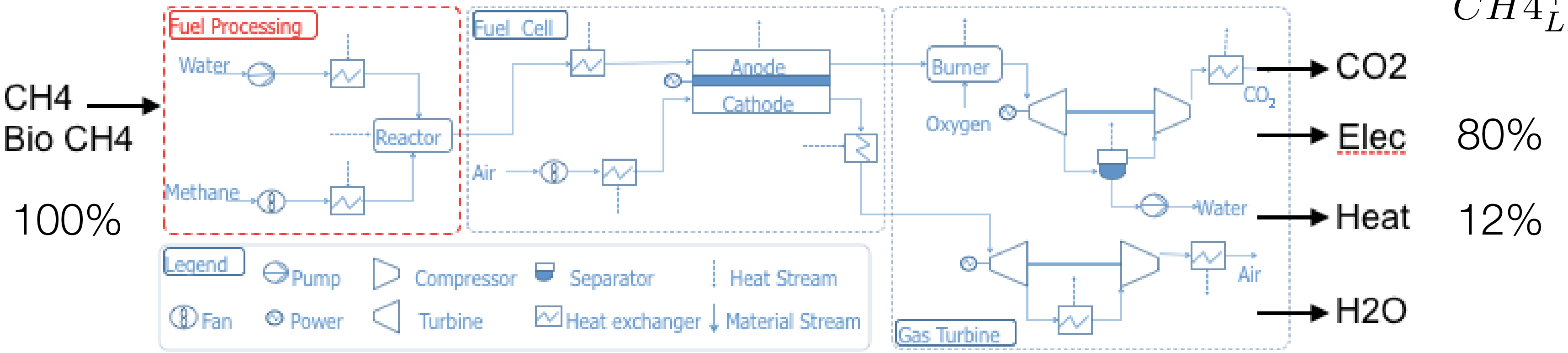
$$\eta = \frac{E^{-}}{E^{+}} = 50\%$$

- **Long term storage on the gas grid !**

If Electricity production efficiency increases

- **Hybrid gas turbine SOFC combined cycle**

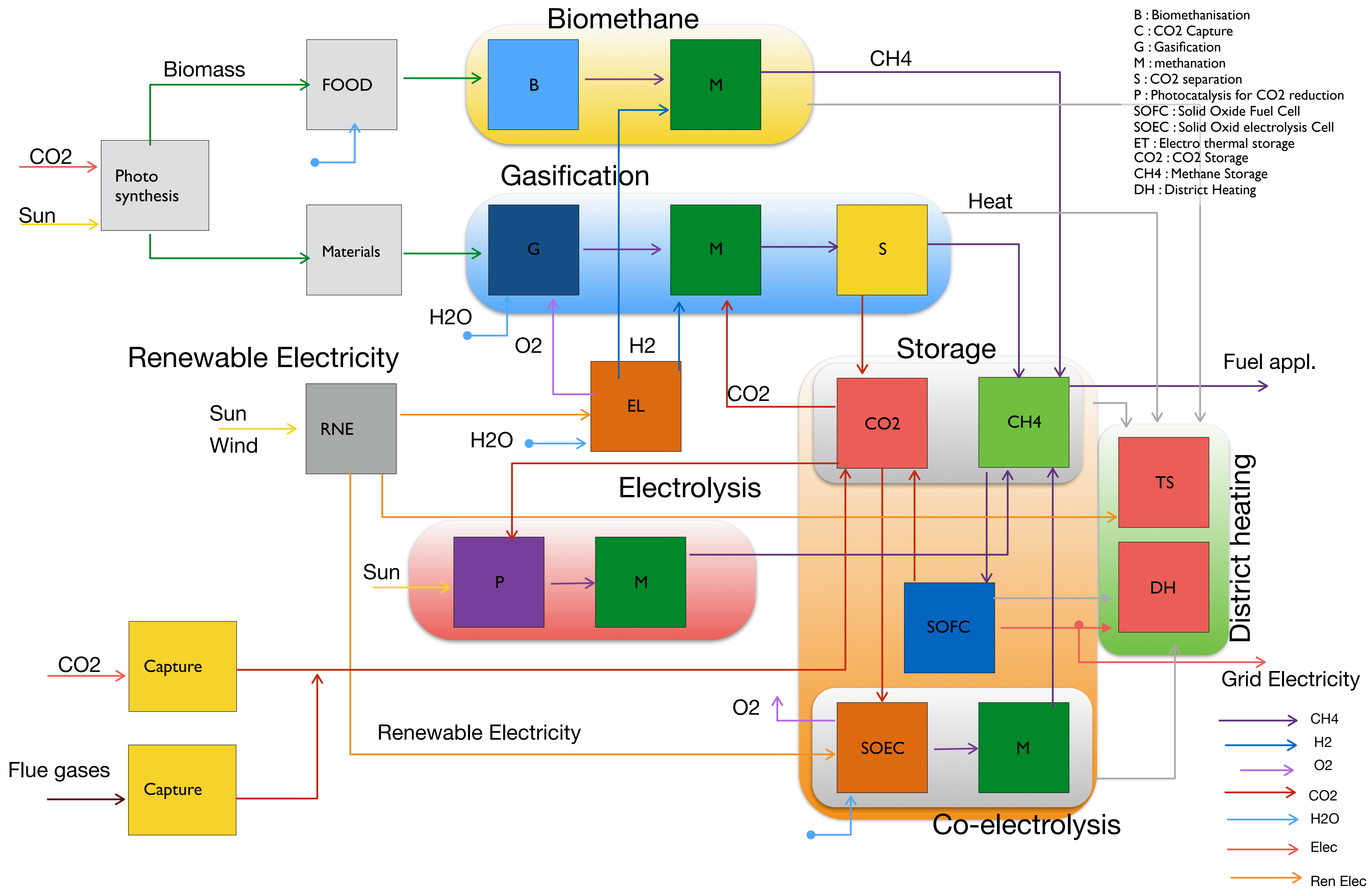
$$\eta_d = \frac{E^-}{CH4^+_{LHV}} = 80\%$$



$$\eta = \frac{E^-}{E^+} = 68\%$$ **A battery is 80%**

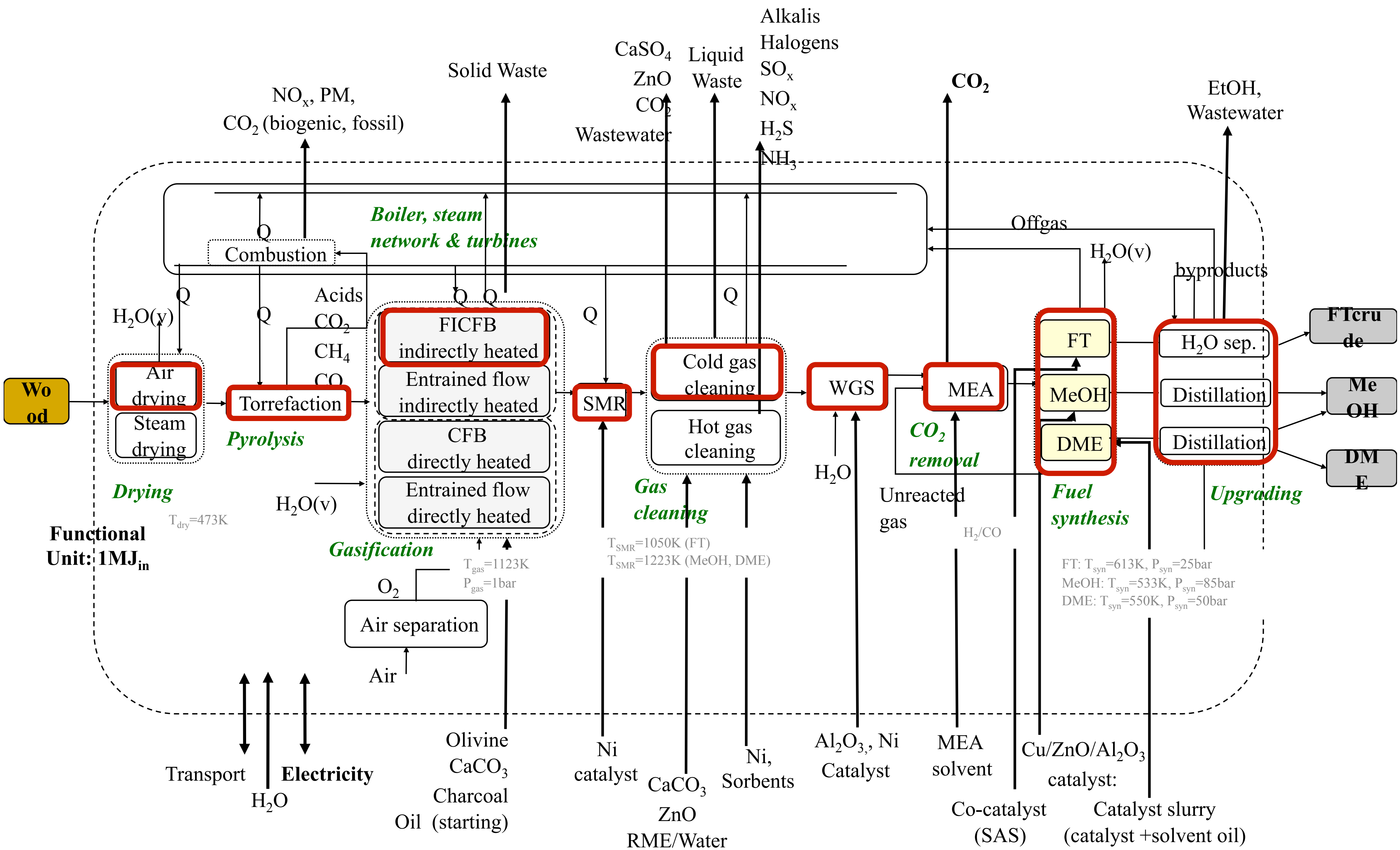
- **Round trip with long term storage on gas grid and decentralised production**

CO2 capture and reuse/electricity storage



- Producing liquid fuels

Process Superstructure



[4]Gassner, M. & Maréchal, F., Thermo-economic process model for the thermochemical production of Synthetic Natural Gas (SNG) from lignocellulosic biomass. *Biomass &Bioenergy, 33(11):1587–1604, 2009.* [5]Tock, L., Gassner, M.& Maréchal, F.,Thermo-economic process model for thermochemical production of liquid fuels from lignocellulosic biomass, submitted to Bomass & Bioenergy 2009.

Fischer – Tropsch process

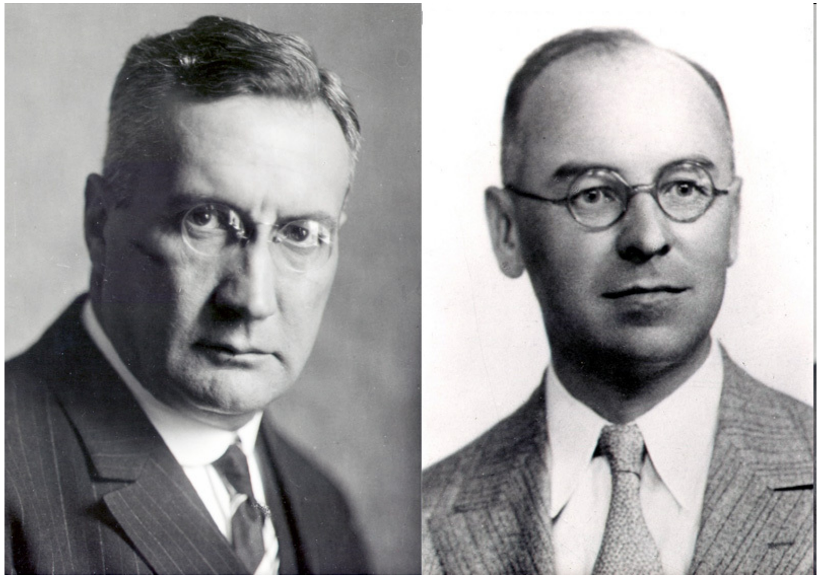


Image: Max Planck Institute of Coal Research.

Franz Fischer and Hans Tropsch developed in Germany in the 1920s

- Historical importance – Fuels from Coal
  - **WWII** – Germany
  - **Apartheid** in South Africa – Sasol

- Drop in Fuel
  - No changes in the infrastructure/fleet

CO →
H_2 →

p, T, t, Catalyst

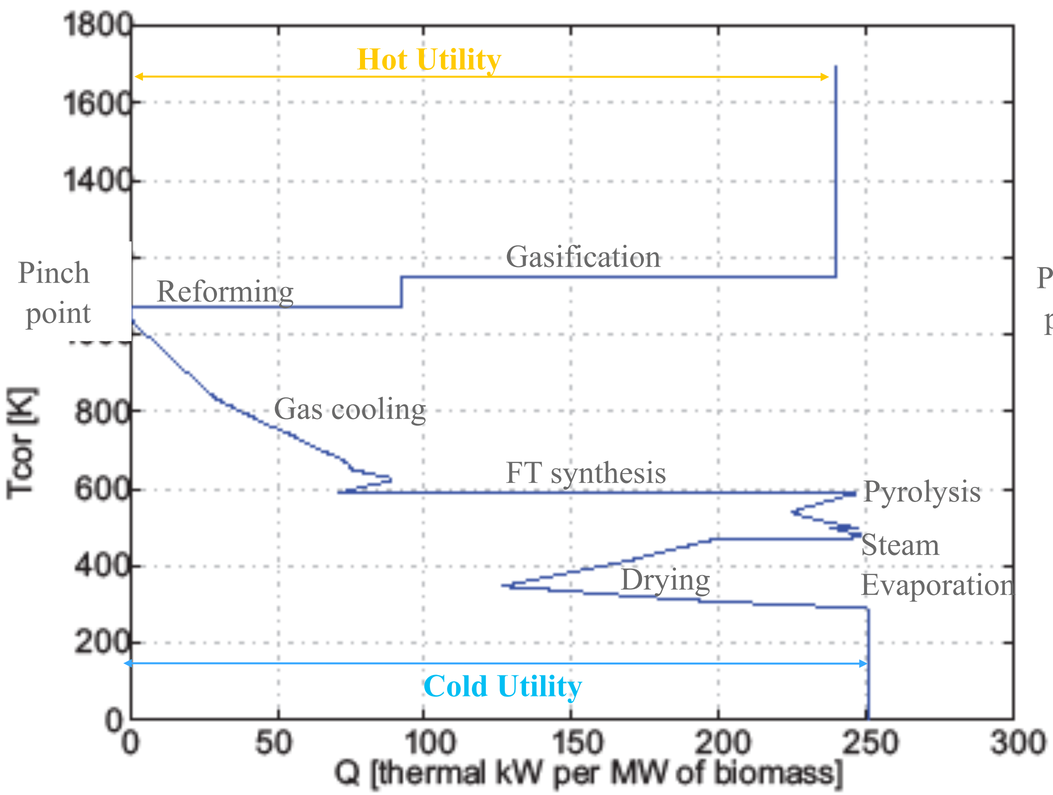
→ CH_4
→ Ammonia
→ **Gasoline, Jet-fuel, Diesel**
→ Wax

$$\mathbf{CO+2H_2 <-> (-CH_2-)(l)+H_2O(l)\ (\Delta H^0=-231.1\ kJ/mol\ {\scriptstyle (1/8\ of\ 1\text{-}octene\ C8H16)})}$$

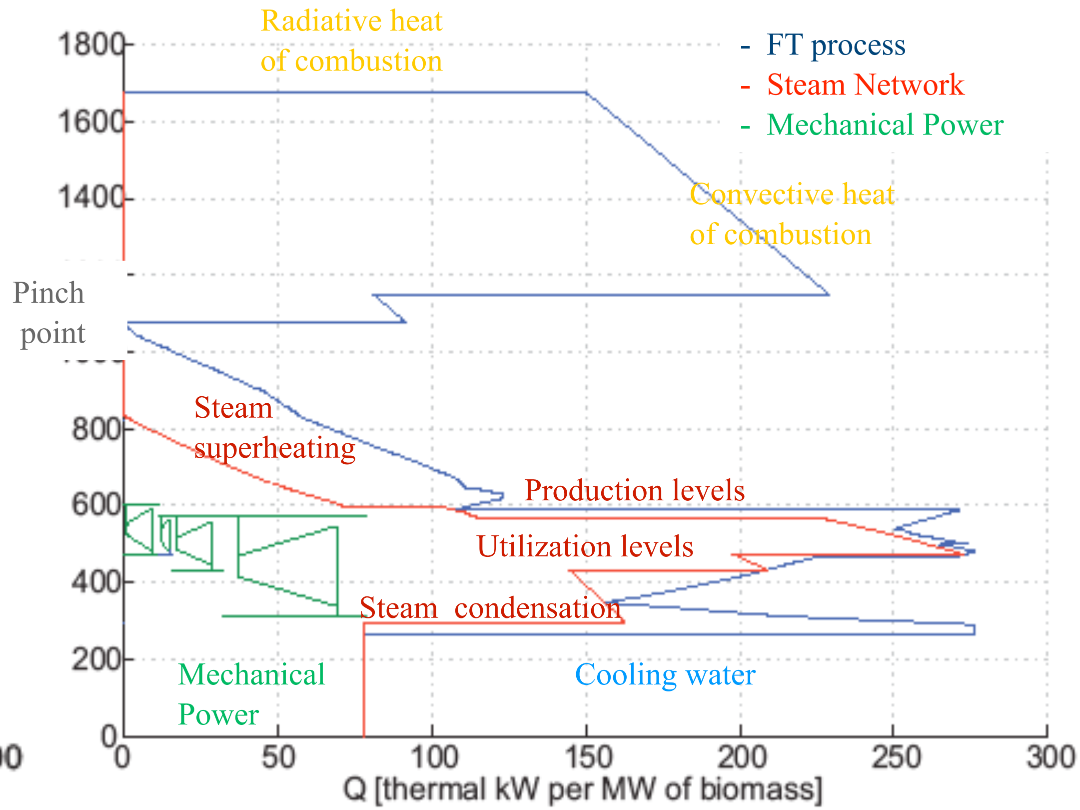
Temperature is controlling the species distribution

Process Performance – Energy Integration

- Maximum heat recovery & heating and cooling requirements for FT process



- Optimal energy conversion & combined heat and power production for FT process



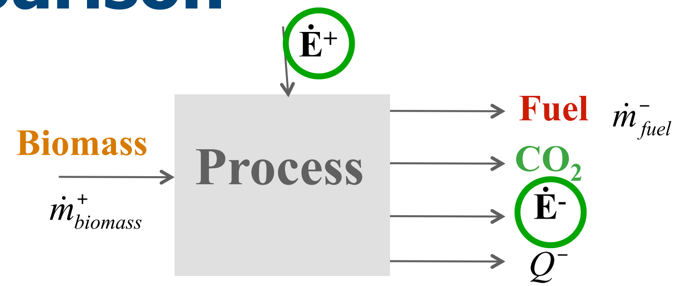
➡ ***Energy performance***

- *Valorize heat excess → Rankine cycle*

➡ ***Steam network***

- *2 production, 2 usage & 1 condensation level → Efficiency increase of **17%***

Process Performance - Comparison



- Performance indicators
  - Overall energy efficiency ε_{tot}
    - Expressed on the basis of the lower heating value of dry substance

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

  - Chemical efficiency ε_{chem}
    - $\dot{E}$ substituted by a natural gas fuel equivalent: NGCC/HP

$$\eta_{NGCC} = \eta_{HP} = 55\%$$

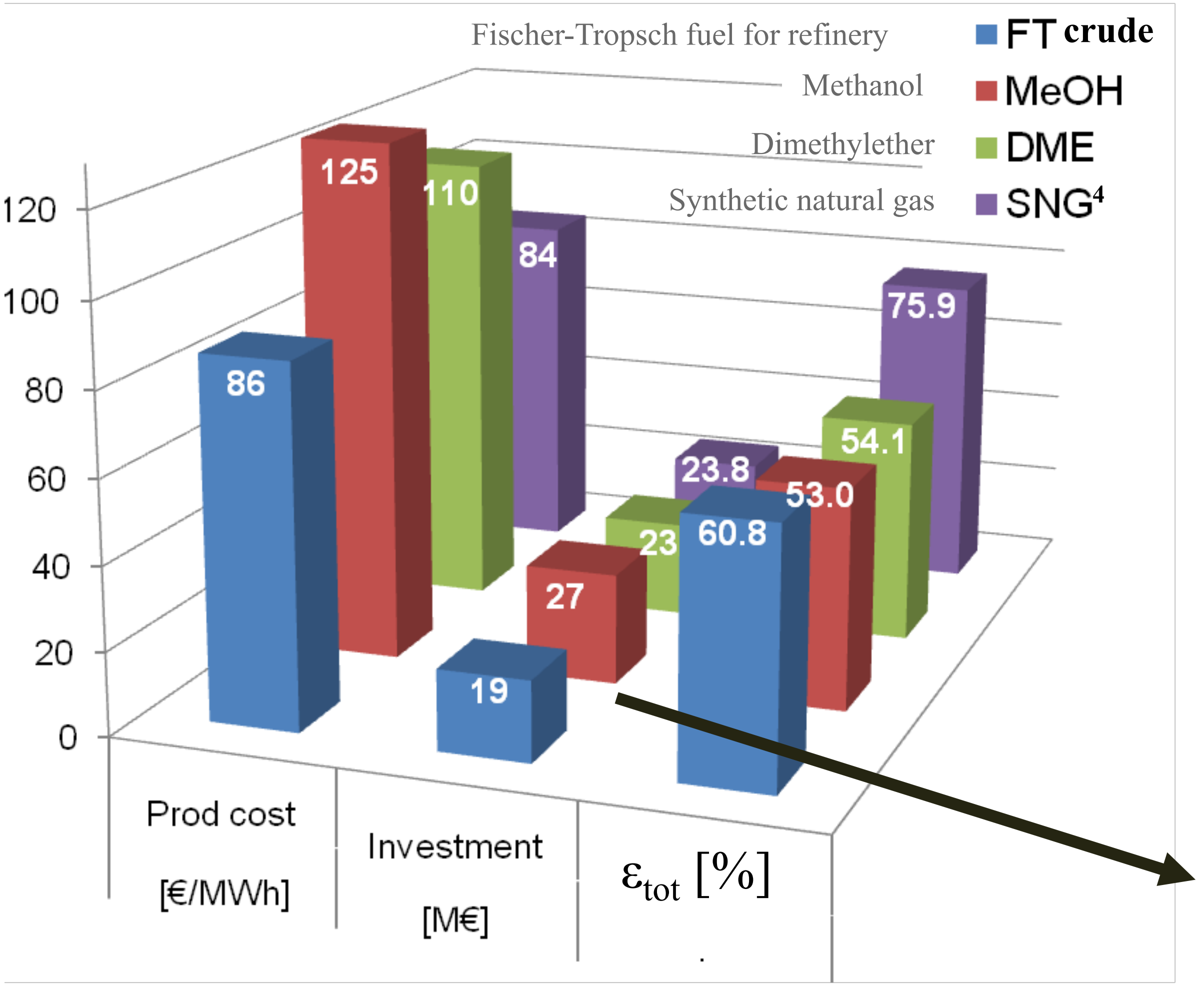
$$\varepsilon_{chem} = \frac{\Delta h^0_{fuel,out} \cdot \dot{m}^-_{fuel} + \frac{1}{\eta_{NGCC}} \frac{\Delta h^0_{SNG}}{\Delta k^0_{SNG}} \left(\frac{1}{\eta_{HP}} \dot{Q}^- + \dot{E}^- \right)}{\Delta h^0_{biomass,in} \cdot \dot{m}^+_{biomass}}$$

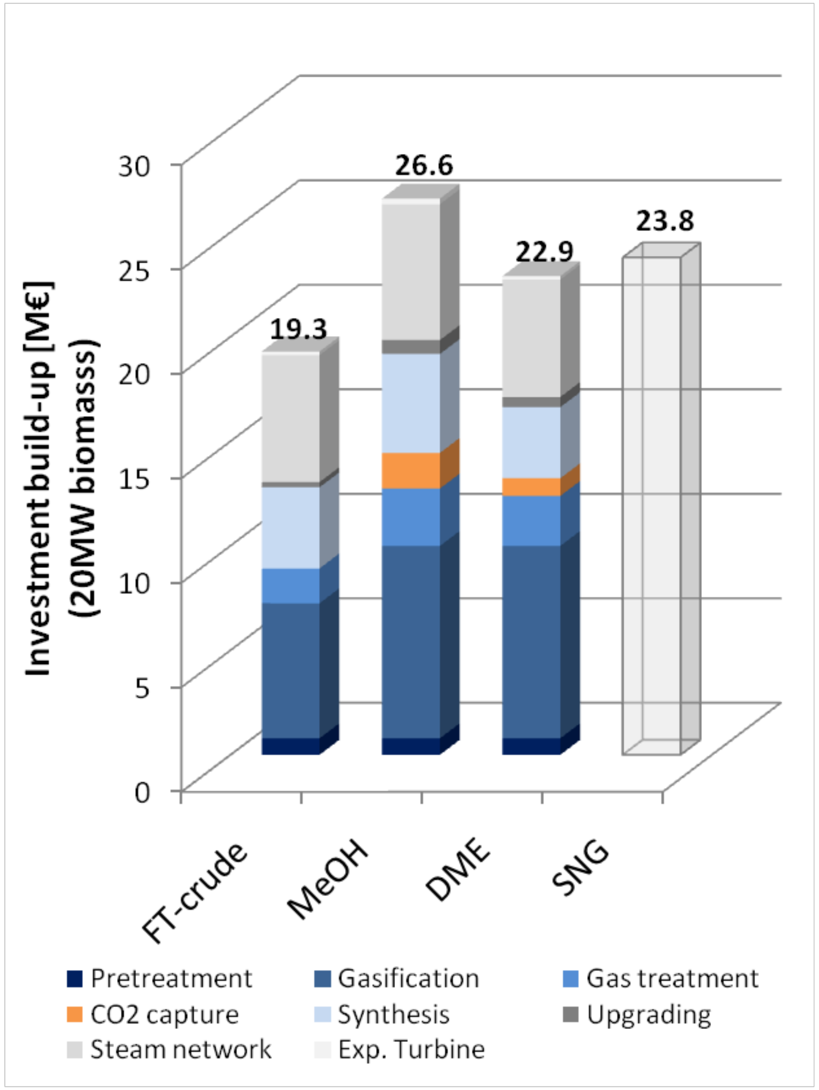
  - Environmental performance
    - Cradle-to-gate LCA approach[5]
    - Impact assessment method: Impact 2002+ method
    - Functional unit: 1MJ of biomass at the installation inlet
  - Plant capacity of $20MW_{th}$ of biomass

[5] Gerber, L., Gassner, M. & Maréchal, F., Integration of LCA in a thermo-economic model for multi-objective optimization of SNG production from woody biomass. In Proceedings of the 19th ESCAPE, Cracow, Poland

Process Performance - Comparison

- Base scenario: indirect fluidized bed gasification, cold gas cleaning

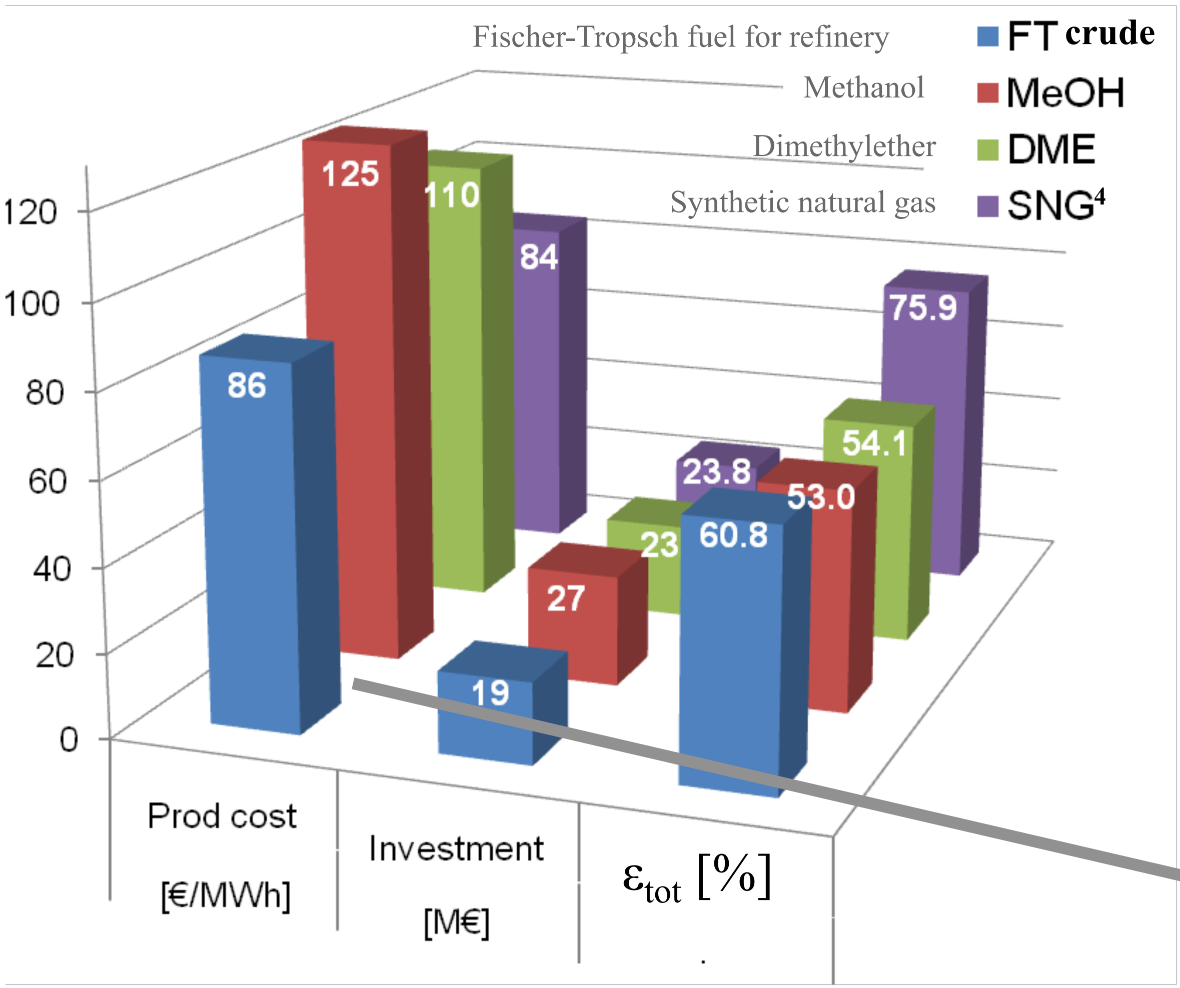


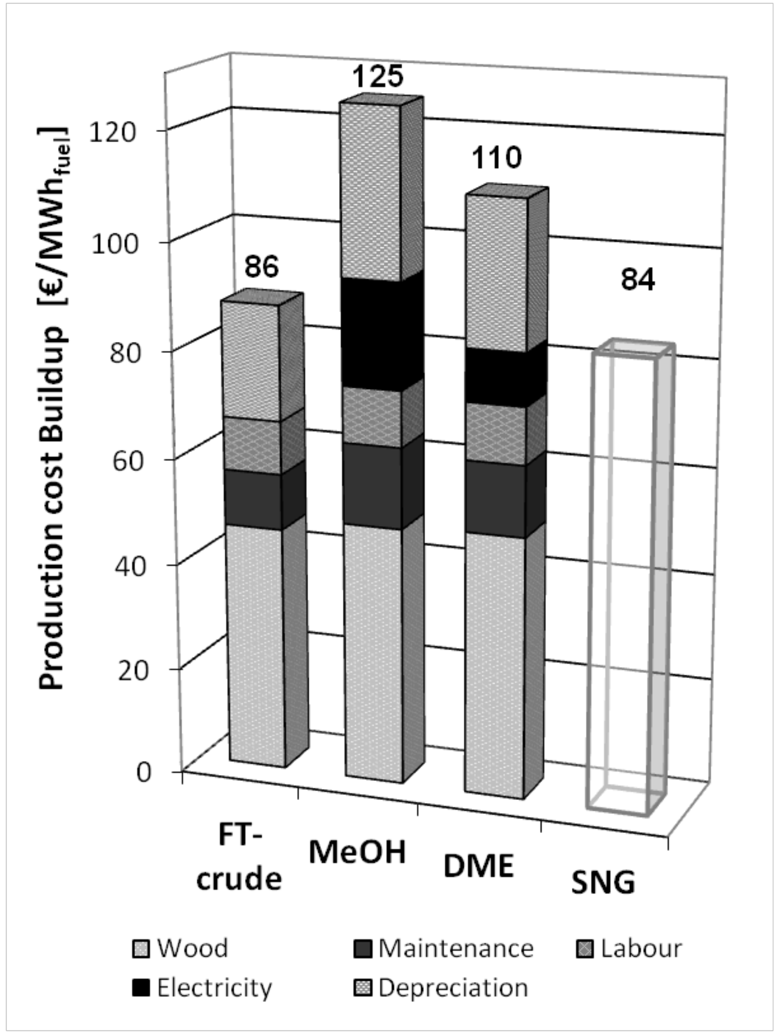


➡ ***FT process highest performance***
- *FT-upgrading not included*
- *No CO_2 removal unit required*
- ***Power demand variation***

Process Performance - Comparison

- Base scenario: indirect fluidized bed gasification, cold gas cleaning



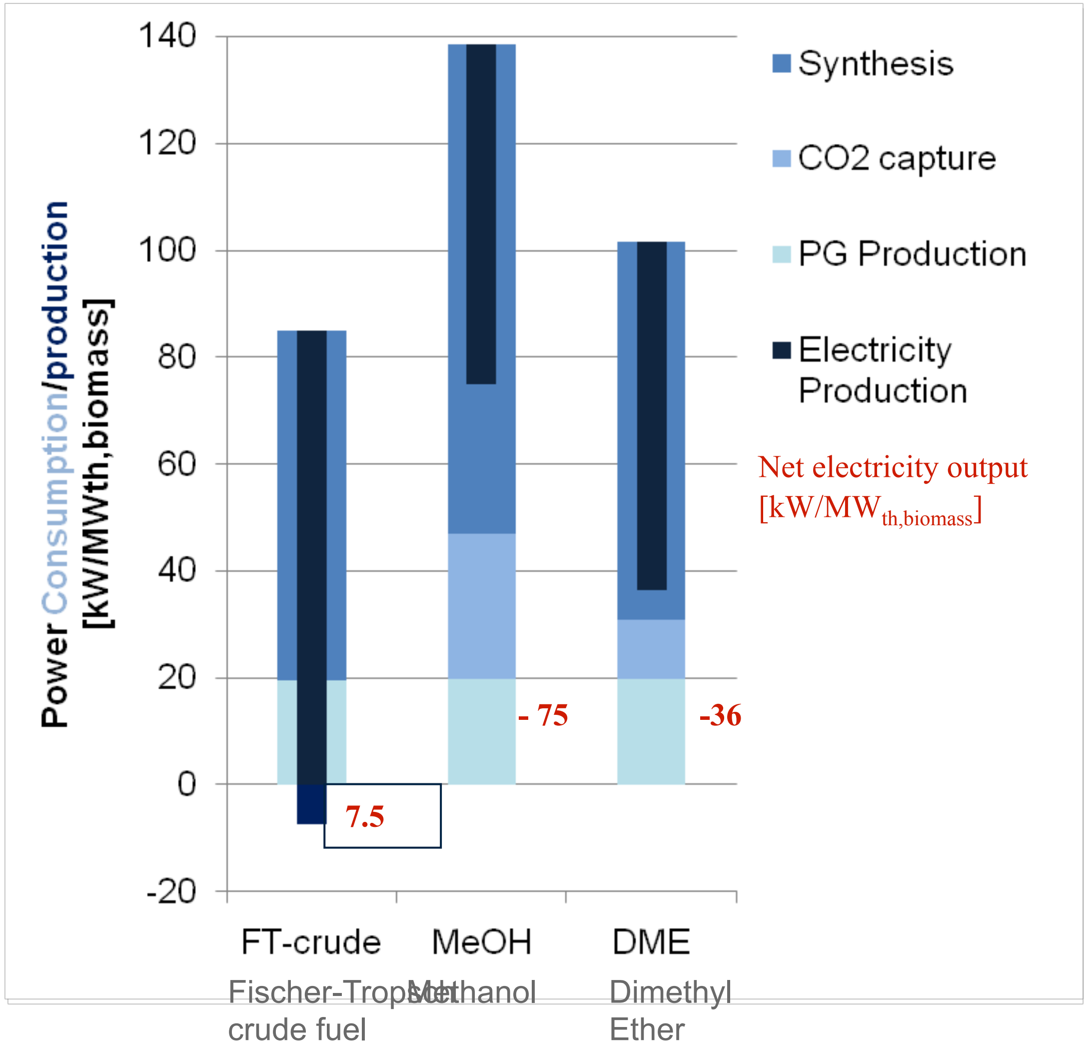


Biomass price: 33 €/MWh[4,5]
Electricity price: 180 €/MWh[4,5]

FT process highest performance
- FT-upgrading not included
- No CO_2 removal unit required
- **Power demand variation**

Process Performance - Comparison

- Base scenario: Power balance

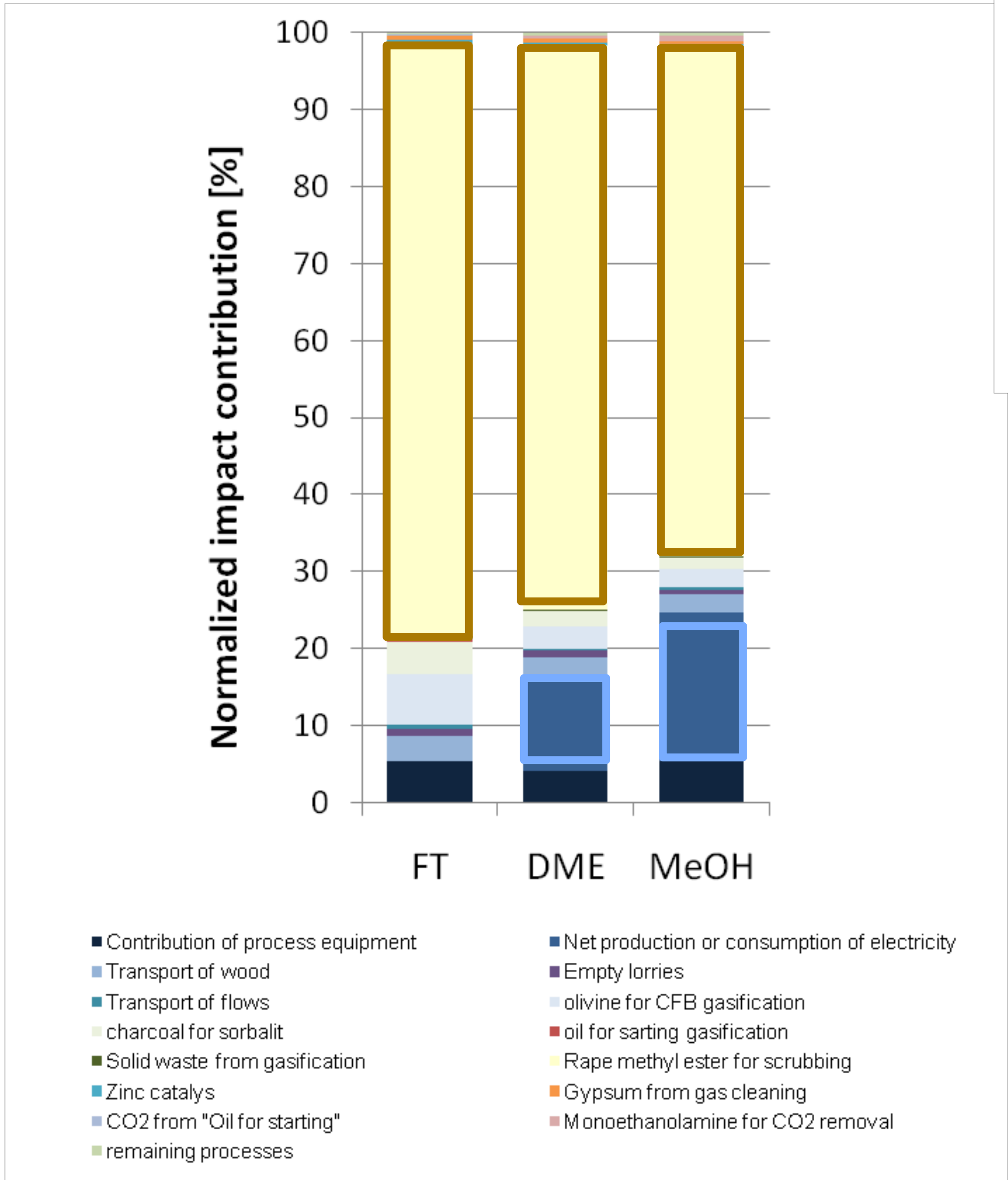


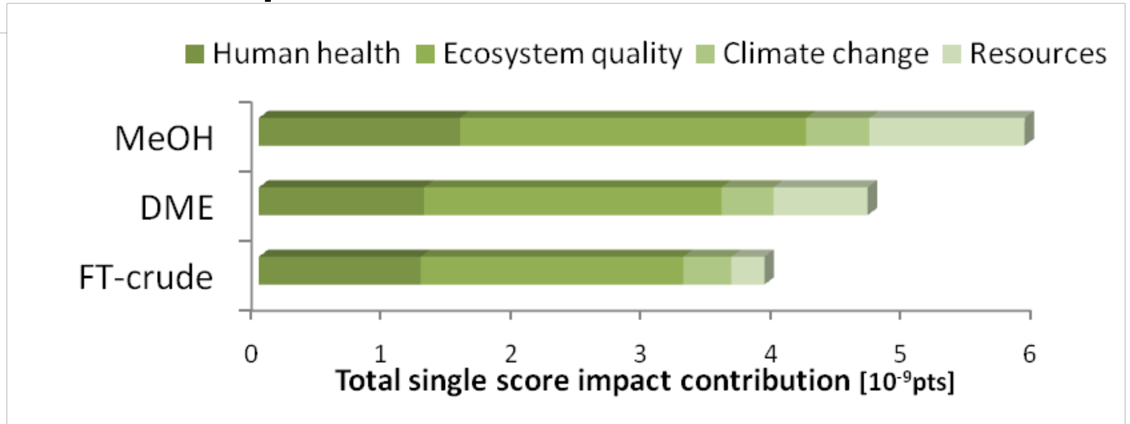
➡ ***Power consumption***
- ***P_{syn}**: FT 25bar, MeOH 85bar, DME 50bar*
- *CO_2 capture: chemical absorption with MEA*

➡ ***Power production***
- ***FT**: Electricity output !*

Process Performance - Comparison

- Competitiveness: Environmental impacts





→ ***Major differences***
- ***Electricity consumption***
  (Swiss mix for medium voltage electricity production at grid)

→ ***Largest impact***
- *Gas cleaning:*
  Rape methyl ester (RME) from rape cultivated with pesticides !

→ ***Process improvements:***
Alternative gas cleaning technologies

Process Performance - Optimization

- Multi-objective optimization (evolutionary algorithm[6])

  FT process

  - Objectives
    - Minimize investment (total grass roots cost) **min TGRC**
    - Maximize chemical efficiency **max ε_{chem}**

  - Decision variables (12 variables)
    - Process operating conditions

      (T_{syn}, P_{syn}, CO-conv, T_{SMR}, T_{dry}, T_{gas})
    - Steam network characteristics

      (production & consumption levels: T, P)

Decision variable	Range
Synthesis P [bar]	20-30
Synthesis T [K]	590-660
CO-conv [%]	82-88
SMR T [K]	950-1200
Drying T [K]	433-513
Humidity drying outlet [%]	5-35
Gasification T [K]	1000-1200
H_2O flow [kg/s/kg PG]	0.06-0.1
1st Prod. level [bar]	60-90
2nd Prod. level [bar]	100-120
Superheating T [K]	623-823
1st Utilization level [K]	323-523

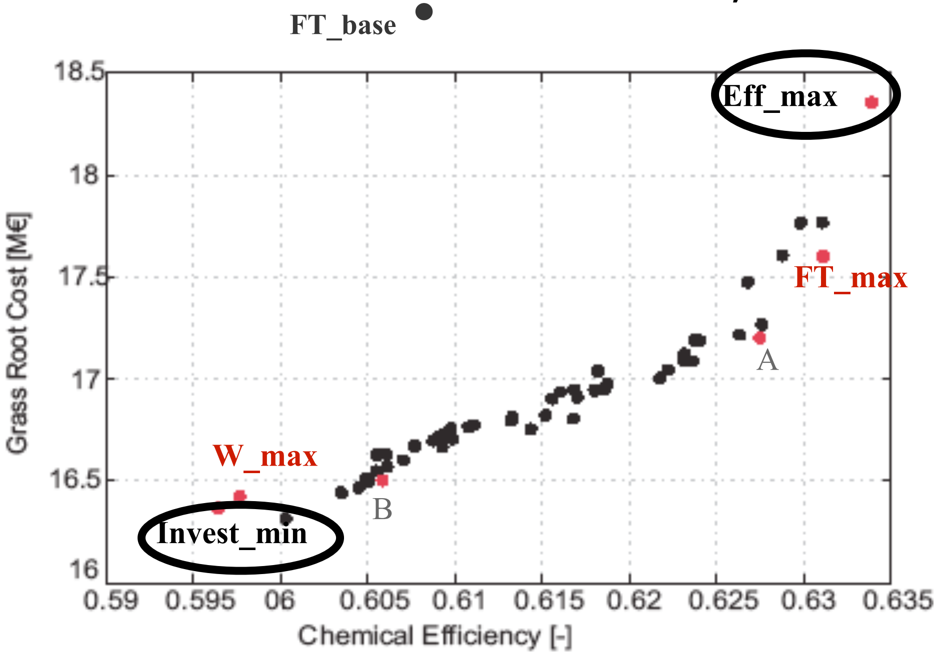
➡ ***Trade-off between competing performance indicators?***

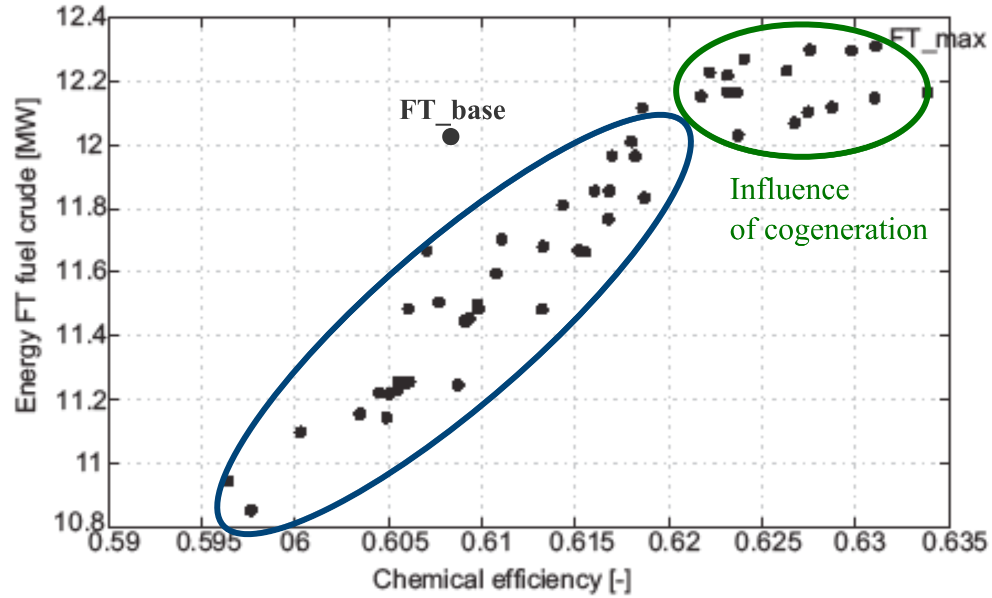
[6] Molyneaux, A; Leyland, G & Favrat, D. (2010), Environomic multi-objective optimisation of a district heating network considering centralized and decentralized heat pumps, *Energy* 35(2) 751-758.

Process Performance - Optimization

- Multi-objective optimization: Pareto optimal frontier

FT process, 20MW$_{th,biomass}$, indirect fluidized bed gasification





➡ *Efficiency* ↗ Investment ↗

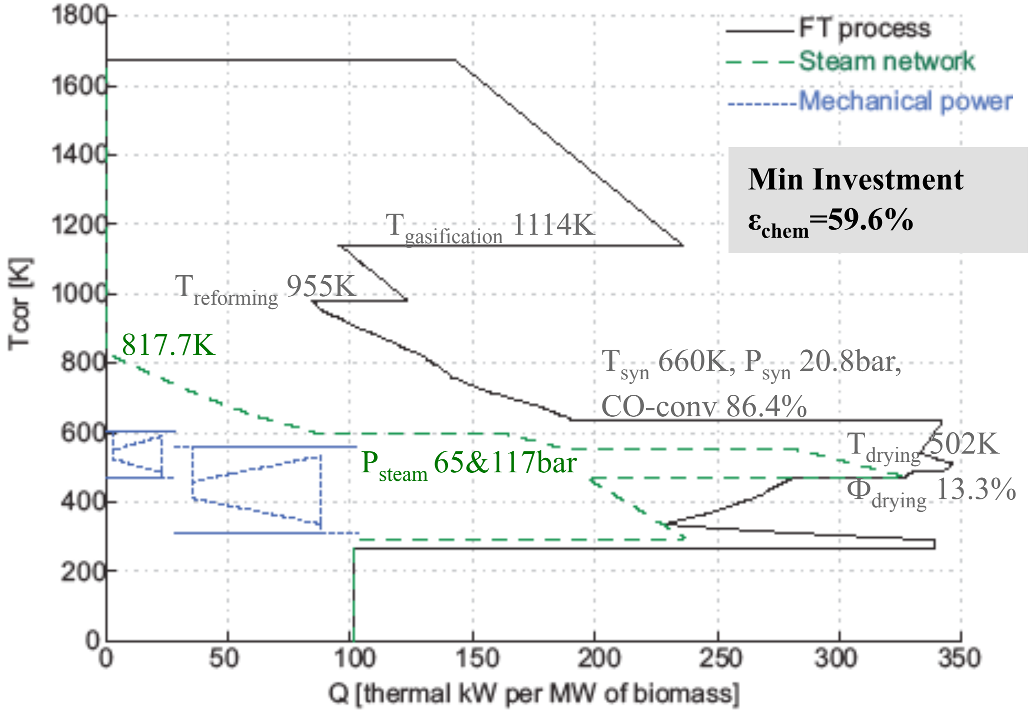
➡ ***Trade-off mechanical power & fuel generation***

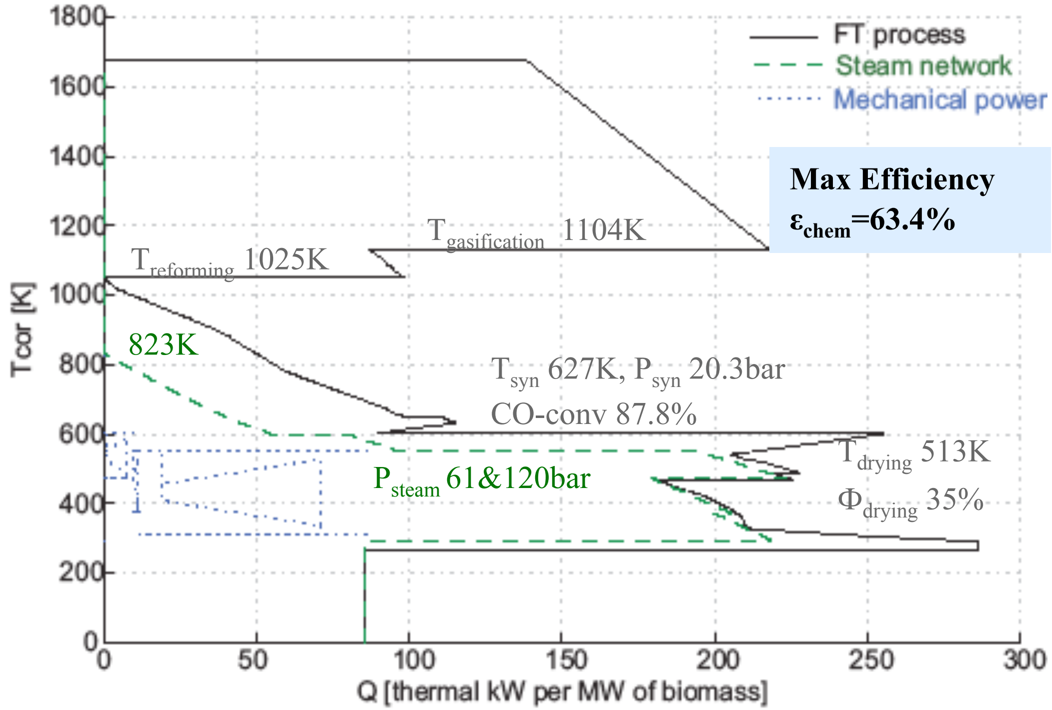
➡ ***Efficiency* ↗ *FT-crude fuel* ↗**

➡ ***Influence of process operating conditions on process integration !***

Process Performance - Optimization

- Energy Integration influence on performance



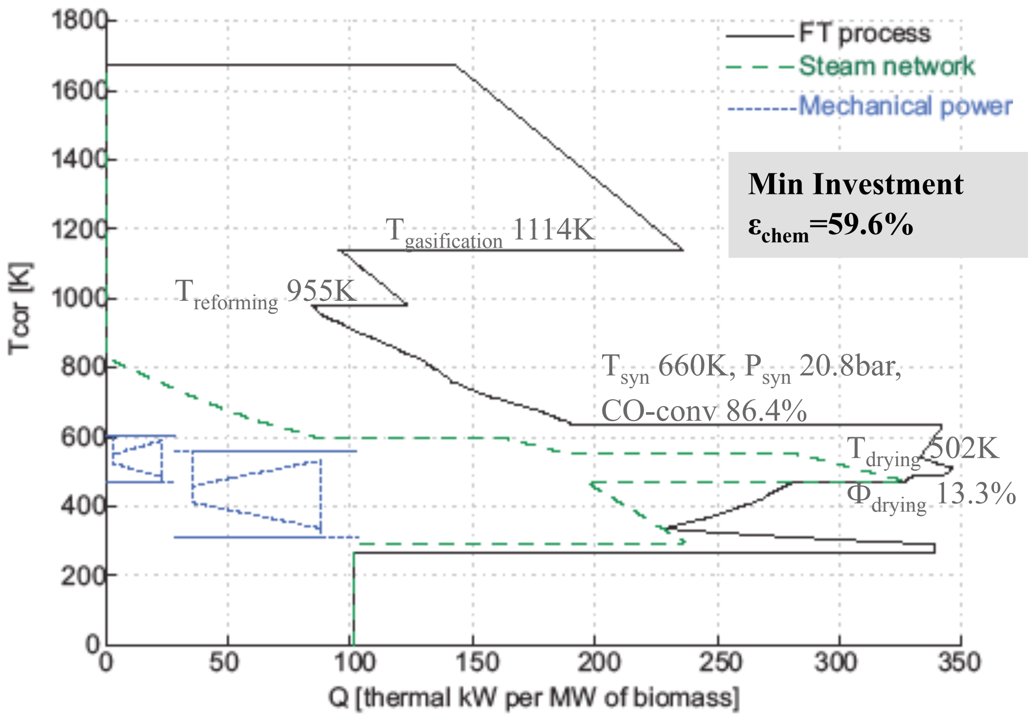


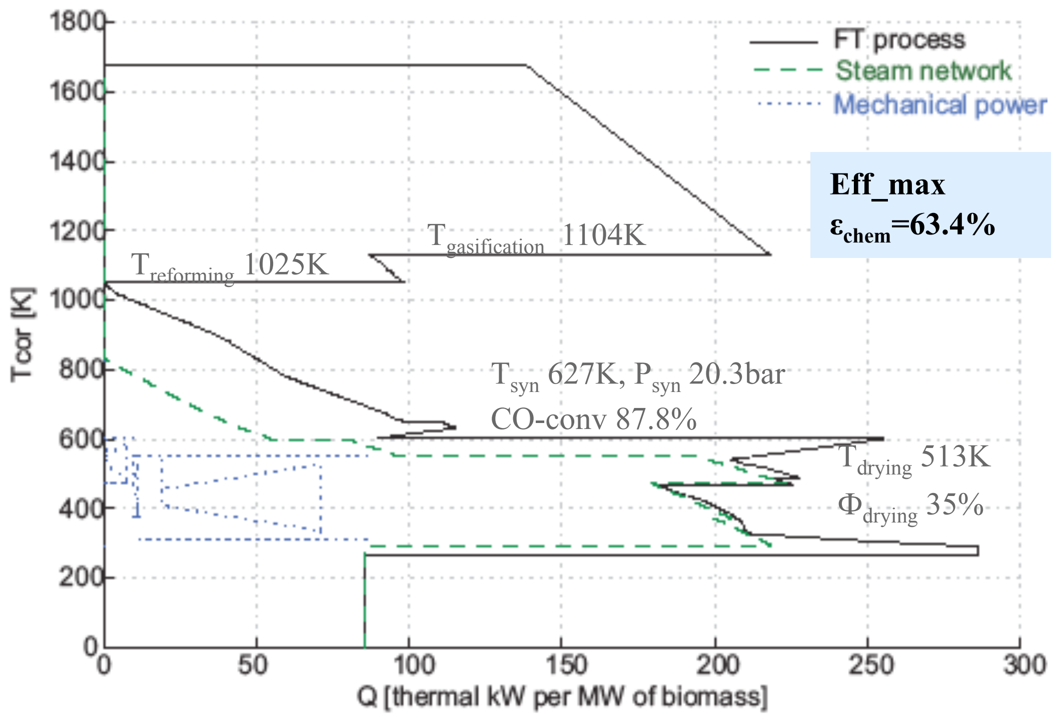
Power balance [kW/MW]	Base case	Min Cost	Max Efficiency
Consumption	85	77	74
Generation	92.5	107	90
Net electricity	7.5	30	16

→ *Steam network well integrated*
Large amount of excess heat recovered

Process Performance Fisher-Tropsh

- Energy Integration influence on performance





Performance	Base case	Min Cost	Max Efficiency
Net electricity [kW/MW]	7.5	30	16
Fuel output [kW/MW]	600	545	610
Investment [k€/MW]	965	815	915
Prod. cost [€/MWh]	86.1	83.1	81.5
Envir. Impact [10^{-9}pts]	3.90	3.13	3.65

→ ***Trade-off: power & fuel production***

→ ***Additional annual fuel production compensates annualized investment impact!***

→ ***Resource impact ↘***
Electricity generated by steam turbine replaces nuclear in Swiss mix

Training on

Technologies for Converting Waste Agricultural Biomass into Energy

Organized by

United Nations Environment Programme (UNEP DTIE IETC)

23-25 September, 2013

San Jose, Costa Rica

Biomass Pyrolysis

Surya Prakash Chandak

Senior Programme Officer

International environmental Technology Centre

Division of Technology, Industry and Economics

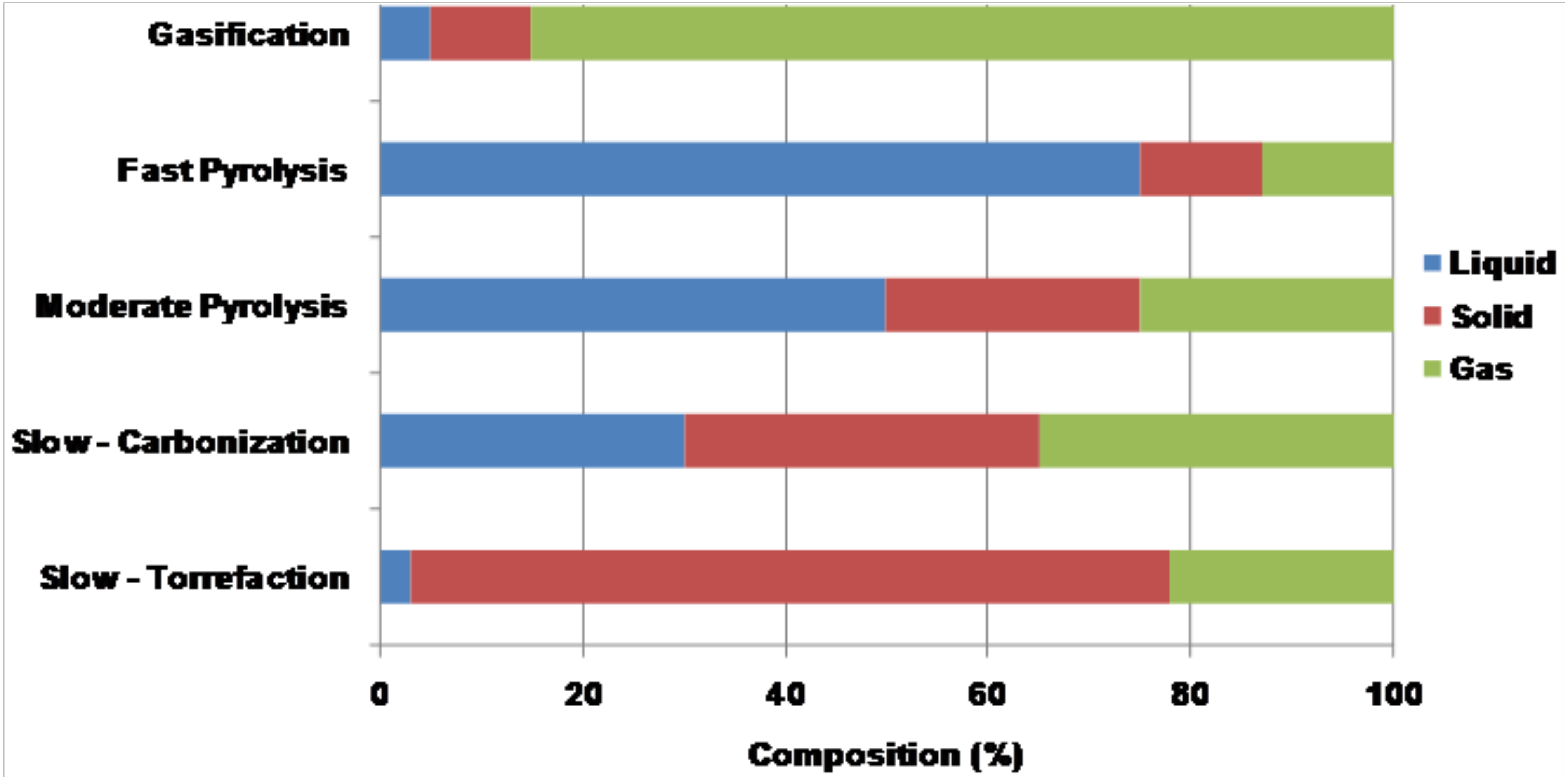
Osaka, Japan

INTRODUCTION

- **Overview**
  - Pyrolysis is defined as irreversible chemical change brought about by heat in the absence of oxygen.
  - During pyrolysis biomass undergoes a sequence of changes and normally yields a mixture of gases, liquids and solid.
  - The solid is called charcoal while the condensable liquid is variously referred to as pyroligneous liquid, pyroligneous liquor, pyroligneous acid or pyrolysis oil. The gas is called producer gas or wood gas.
  - Generally low temperatures and show heating rates results in high yield of charcoal. This type of pyrolysis is called carbonization

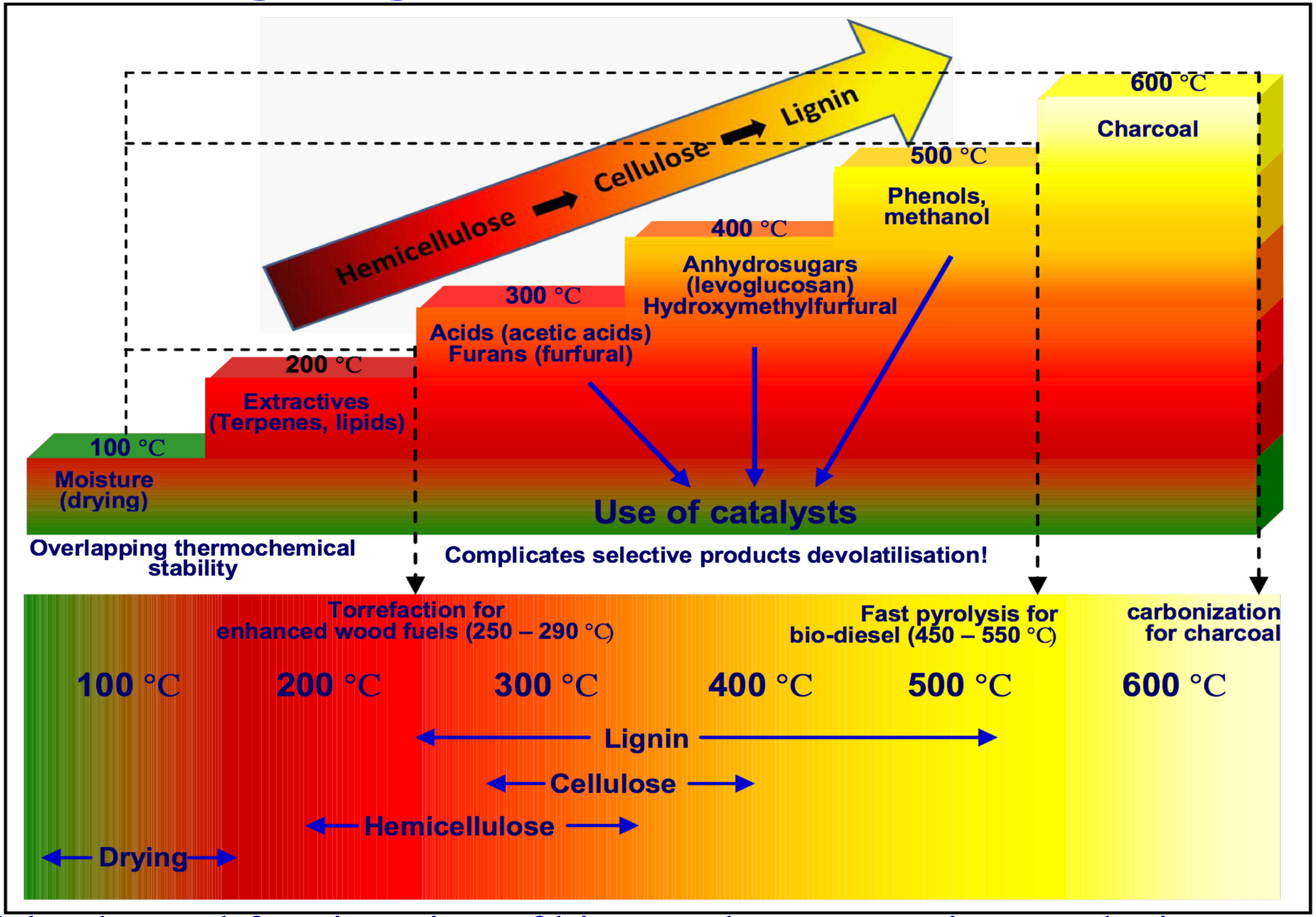
INTRODUCTION

- **Overview**
  - Percentage composition of liquid, solid and gaseous products of different pyrolysis modes



MECHANISM AND PRODUCTS OF BIOMASS PYROLYSIS

- **Biomass Pyrolysis**

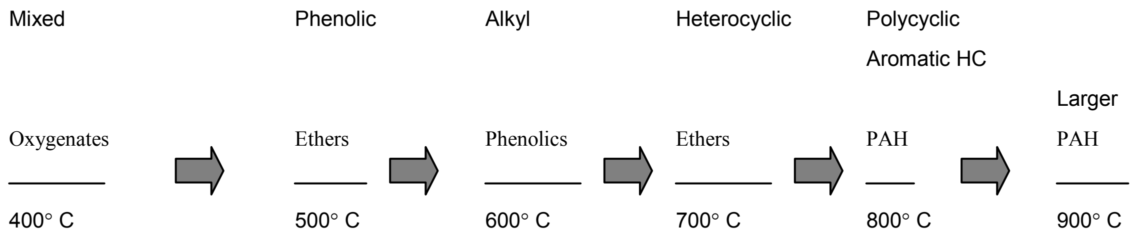


Overview of the thermal fractionation of biomass by a step-wise pyrolysis approach.

Properties of bio-oil

Table 2. Properties of Bio-oil from Various Feedstocks

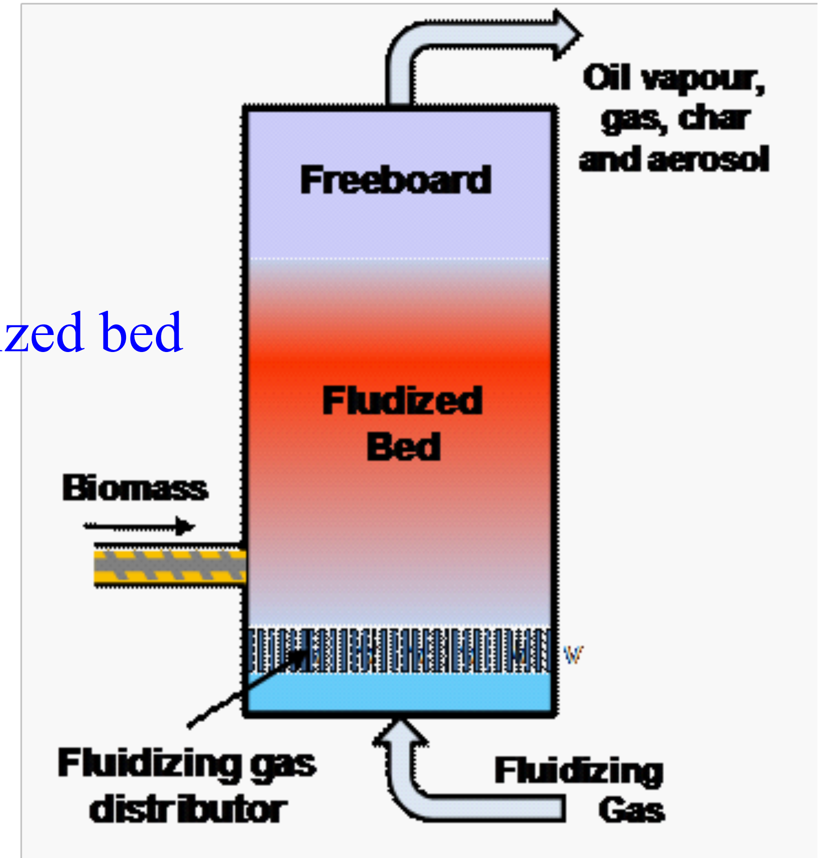
Property	Birch	Pine	Poplar	Various
Solids (wt%)	0.06	0.03	0.045	0.01-1
PH	2.5	2.4	2.8	2.0-3.7
Water (wt%)	18.9	17.0	16.8	15-30
Density (kg/m^3)	1.25	1.24	1.20	1.2-1.3
Viscosity, cSt @ 50°C	28	28	13.5	13-80
LHV (MJ/kg)	16.5	17.2	17.3	13-18
Ash (wt%)	0.004	0.03	0.007	0.004-0.3
CCR (wt%)	20	16	N/M	14-23
C (wt%)	44.0	45.7	48.1	32-49
H (wt%)	6.9	7.0	5.3	6.9-8.6
N (wt%)	<0.1	<0.1	0.14	0.0-0.2
S (wt%)	0.00	0.02	0.04	0.0-0.05
O (wt%)	49.0	47.0	46.1	44-60
Na + K (ppm)	29	22	2	5-500
Ca (ppm)	50	23	1	4-600
Mg (ppm)	12	5	0.7	N/M
Flash Point (°C)	62	95	64	50-100
Pour Point (°C)	-24	-19	N/M	-36 -9



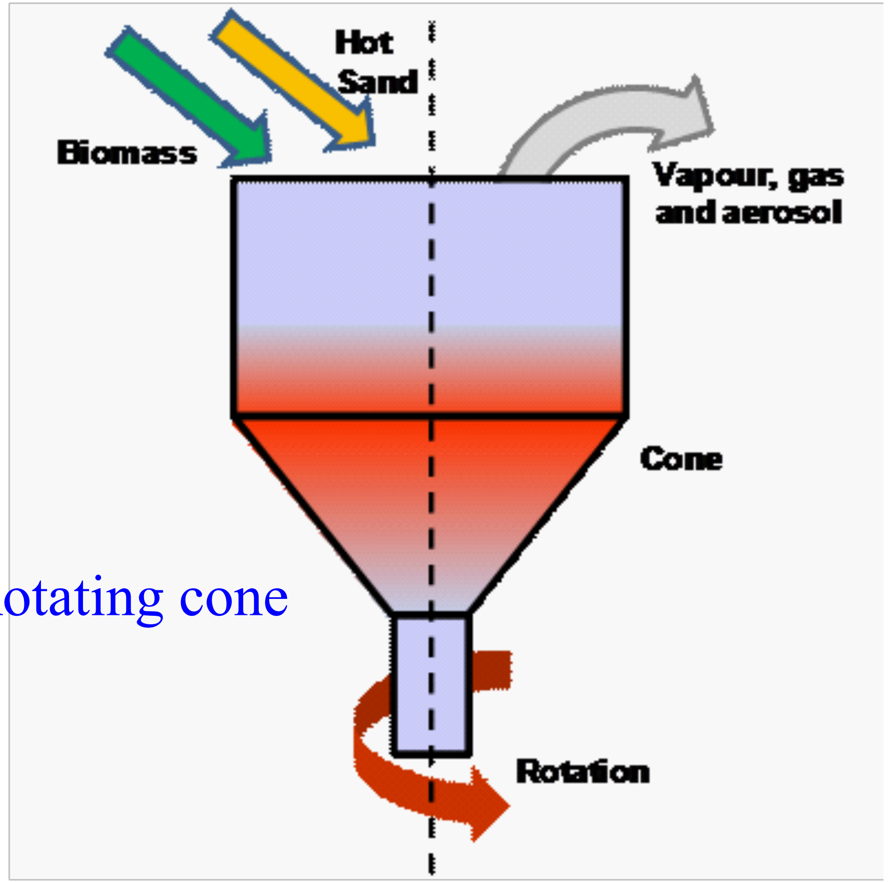
Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis
M. Ringer, V. Putsche, and J. Scahill Prepared under Task No. BB06.7510
Technical Report NREL/TP-510-37779 November 2006

TYPES OF PYROLYTIC REACTORS

- **Types of Pyrolysis Reactor Designs**
  - A number of different pyrolysis reactor designs are available.
  - These include Fluidized bed, Re-circulating fluidized bed, Ablative, Rotating cone, Auger (or screw), Vacuum, Transported bed, and Entrained flow.



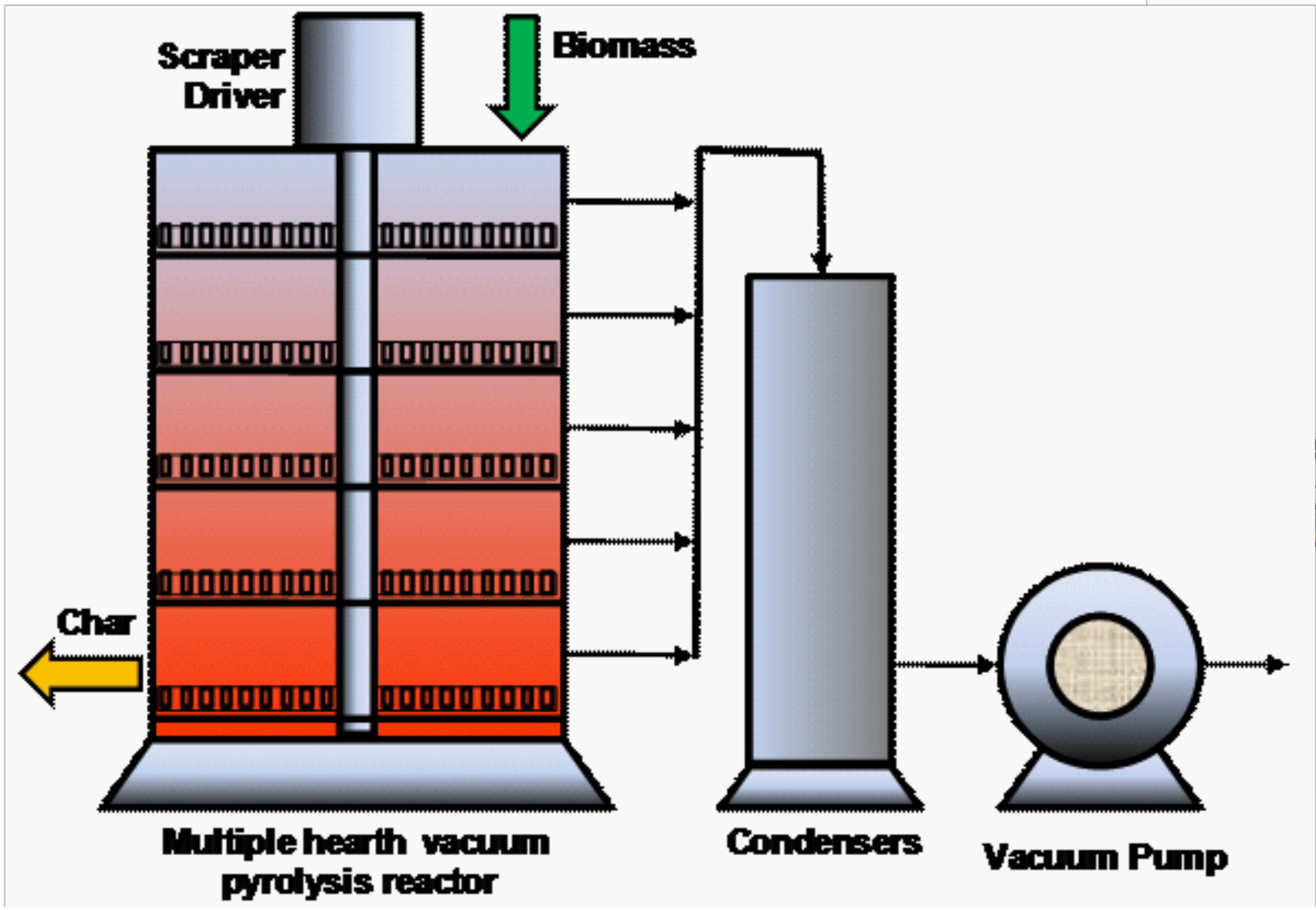
Fluidized bed

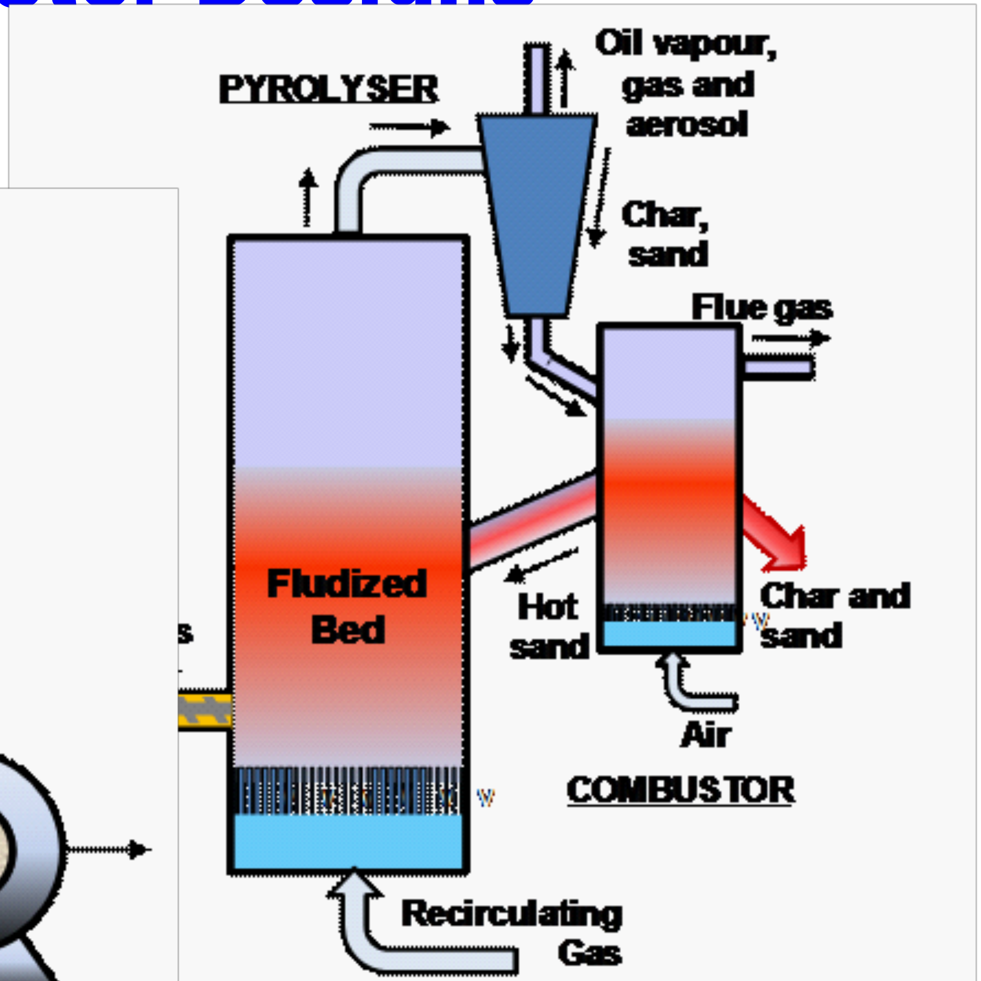


Rotating cone

TYPES OF PYROLYTIC REACTORS

- **Types of Pyrolysis Reactor Designs**

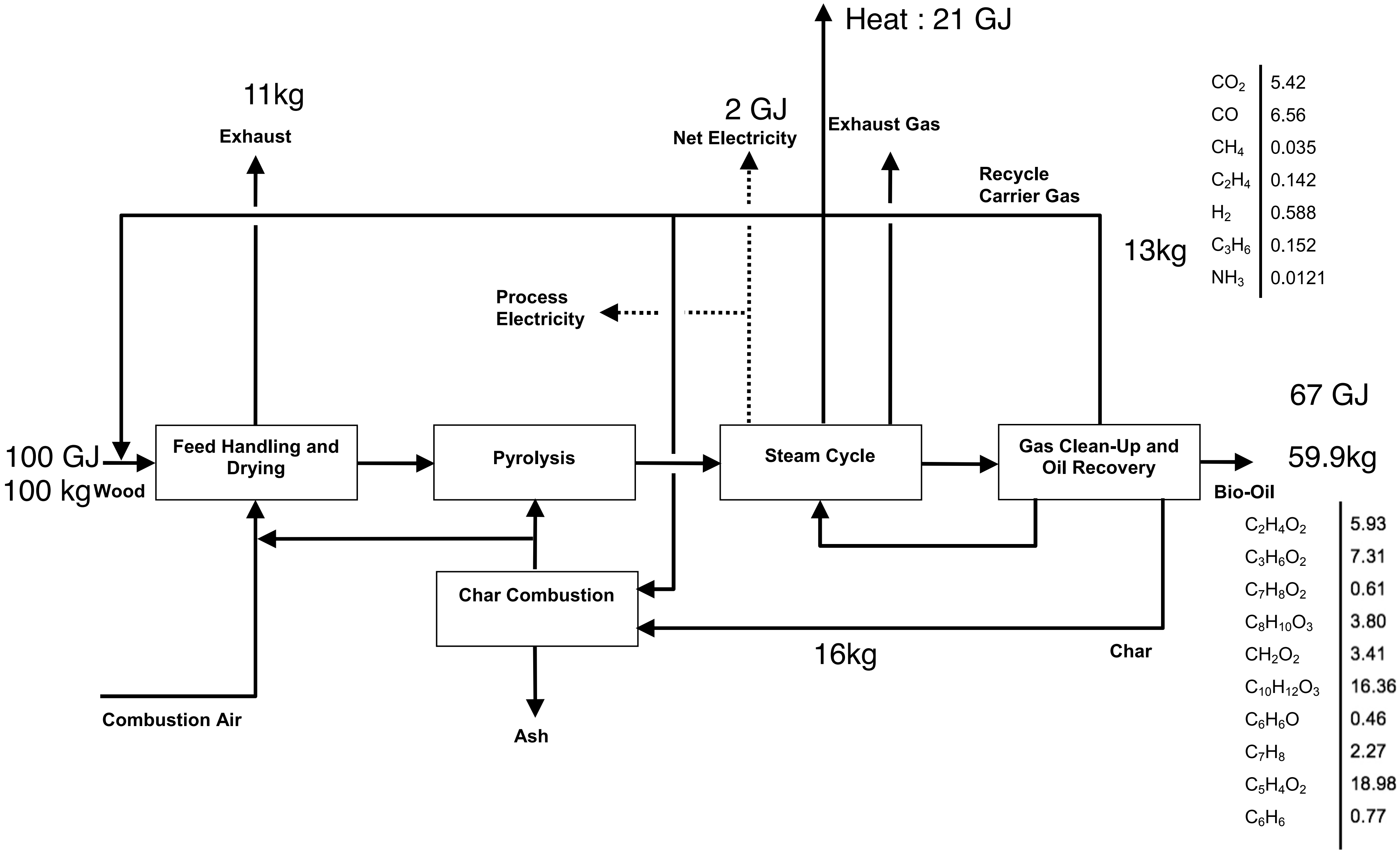




Re-circulating fluidized bed

Vacuum

Typical pyrolysis process



Pyrolysis processes

- Difficulties
  - Fuel specifications (control of the quality and the distribution of components)
    - Difficult to use in conventional engines
    - Integrate in refineries
  - Minerals
  - Stabilisation of bio-Oil
    - Hydrogenation

Examples of pyrolysis processes

Table 12. Worldwide Current Biomass Pyrolysis Operating Plants

Reactor Design	Capacity (Dry Biomass Feed)	Organization or Company
Fluidized bed	400 kg/hr (11 tons/day)	DynaMotive, Canada
	250 kg/hr (6.6 tons/day)	Wellman, UK
	20 kg/ hr (0.5 tons/day)	RTI, Canada
Circulating Fluidized Bed	1500 kg/hr (40 tons/day)	Red Arrow, WI; Ensyn design
	1700 kg/hr (45 tons/day)	Red Arrow, WI; Ensyn design
	20 kg/hr (0.5 tons/day)	VTT, Finland; Ensyn design
Rotating Cone	200 kg/hr (5.3 tons/day)	BTG, Netherlands
Vacuum	3500 kg/hr (93 tons/day)	Pyrovac, Canada
Other Types	350 kg/hr (9.3 tons/day)	Fortum, Finland

Conclusion

- Burning wood is not the only solution
  - conversion in fuels => distribution and storage
  - Densification & transport
- Biomass Conversion
  - Bio SNG and Liquid Fuels
    - exothermic => cogeneration
  - Fuel cell integration
  - CO2 separation
- Power to gas concepts
  - Long term electricity storage by electrolysis integration