# Thermochemical conversion of Biomass

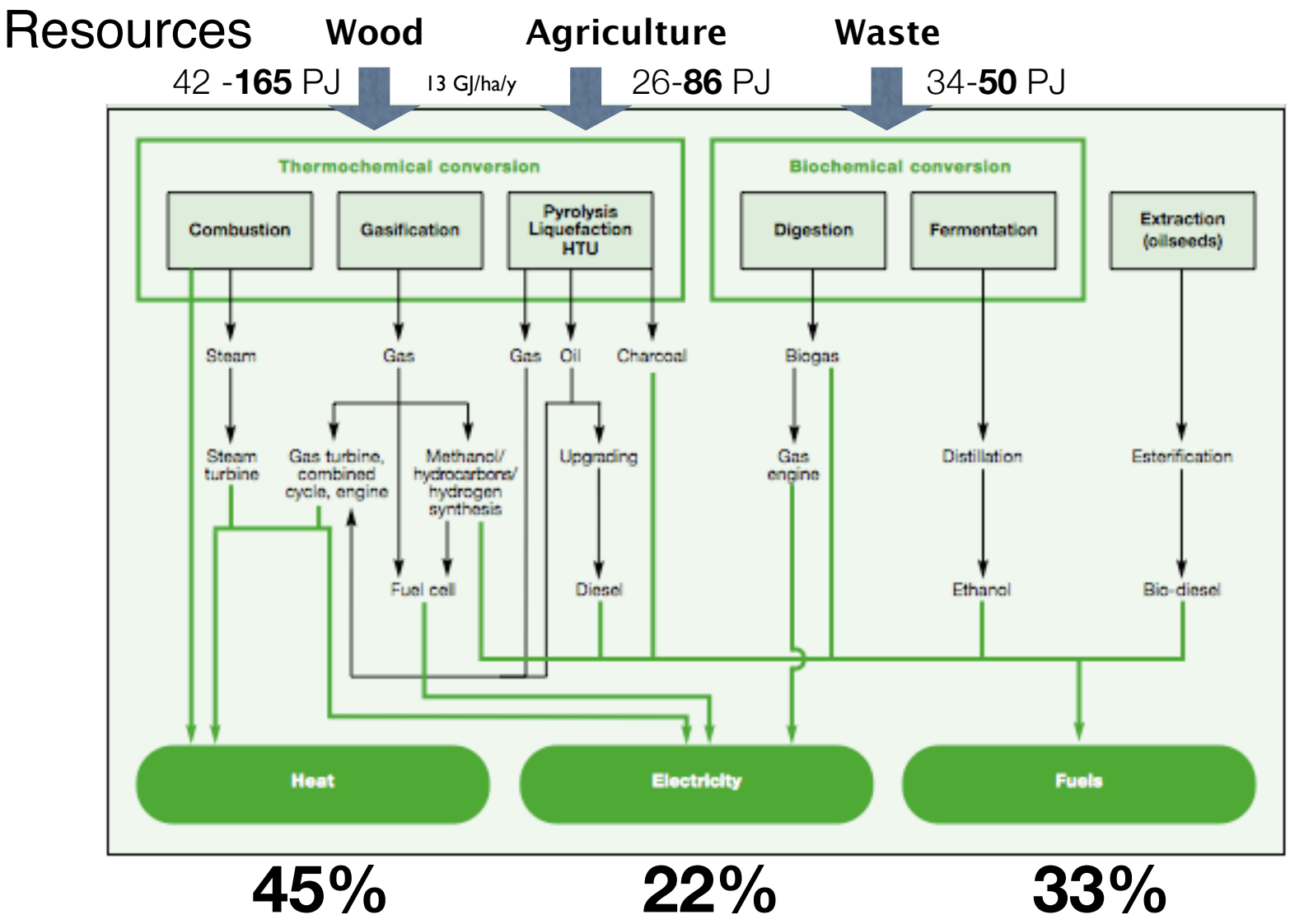
## Gasification

Prof. François Maréchal

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

# Biomass conversion routes and production potential in Switzerland

sustainable -**Technical** in PJ/year

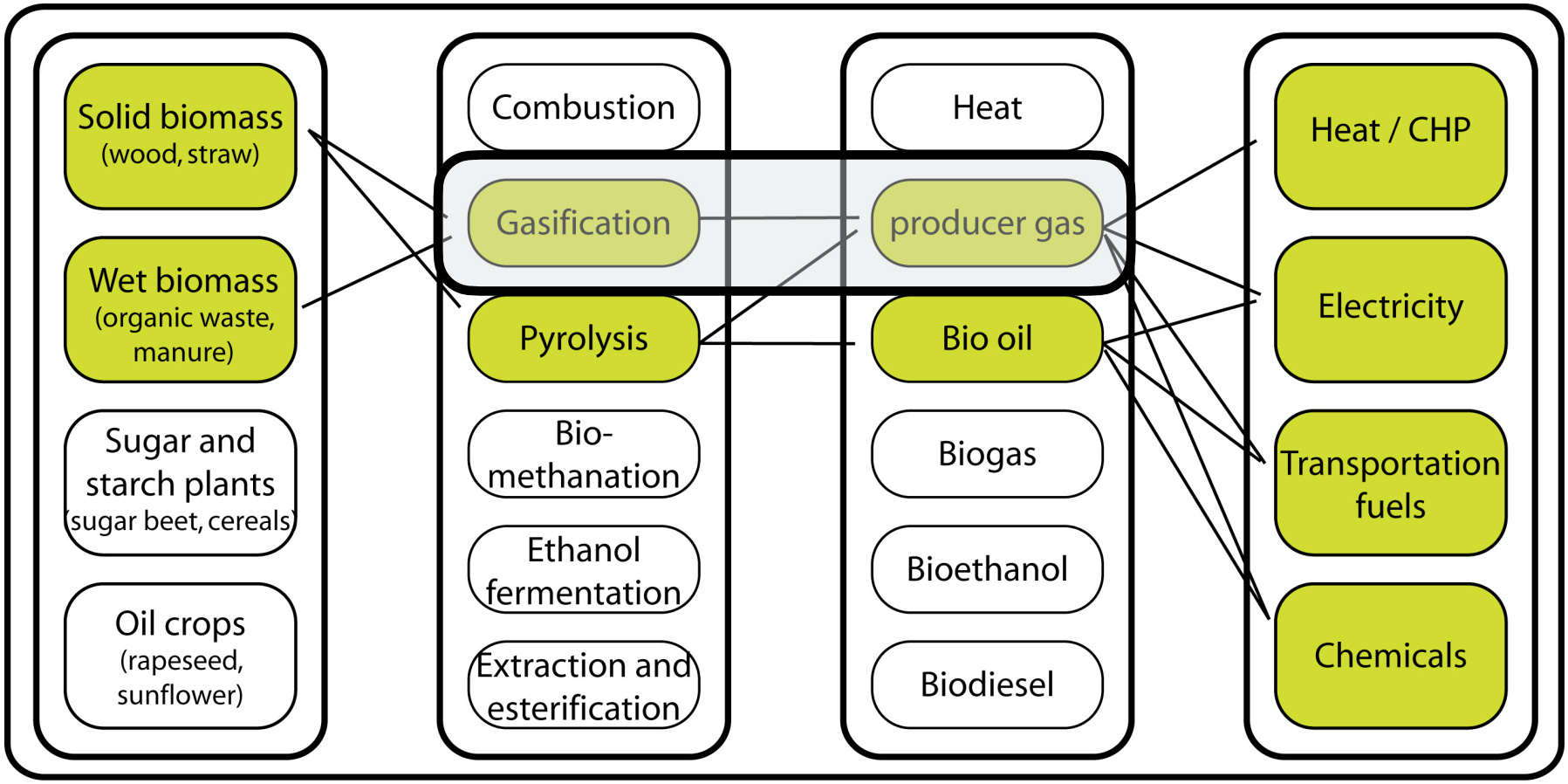



Figures for Switzerland (sustainable potential : total = 82-301 PJ)

**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

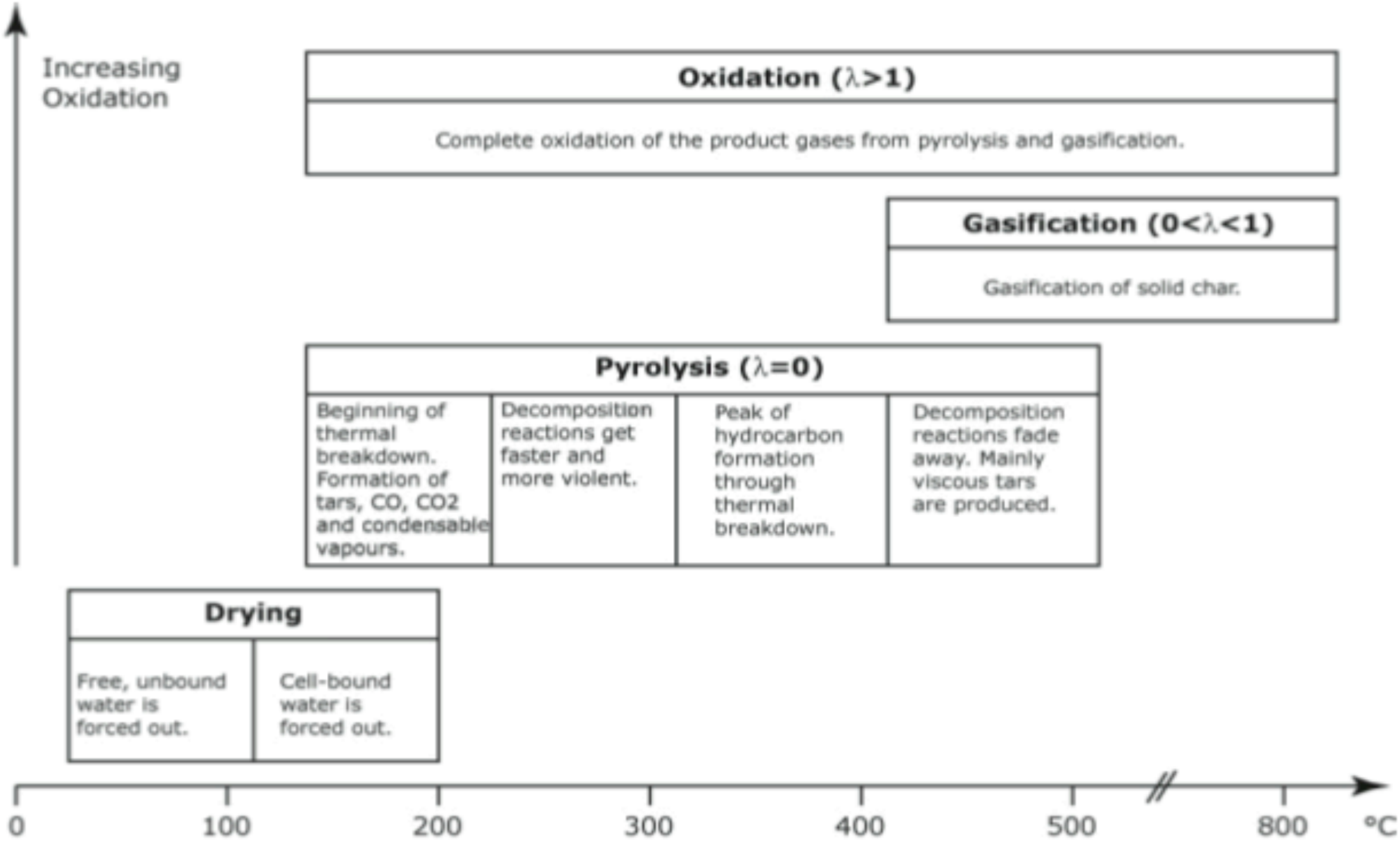
# Biomass conversion
## Thermochemical routes



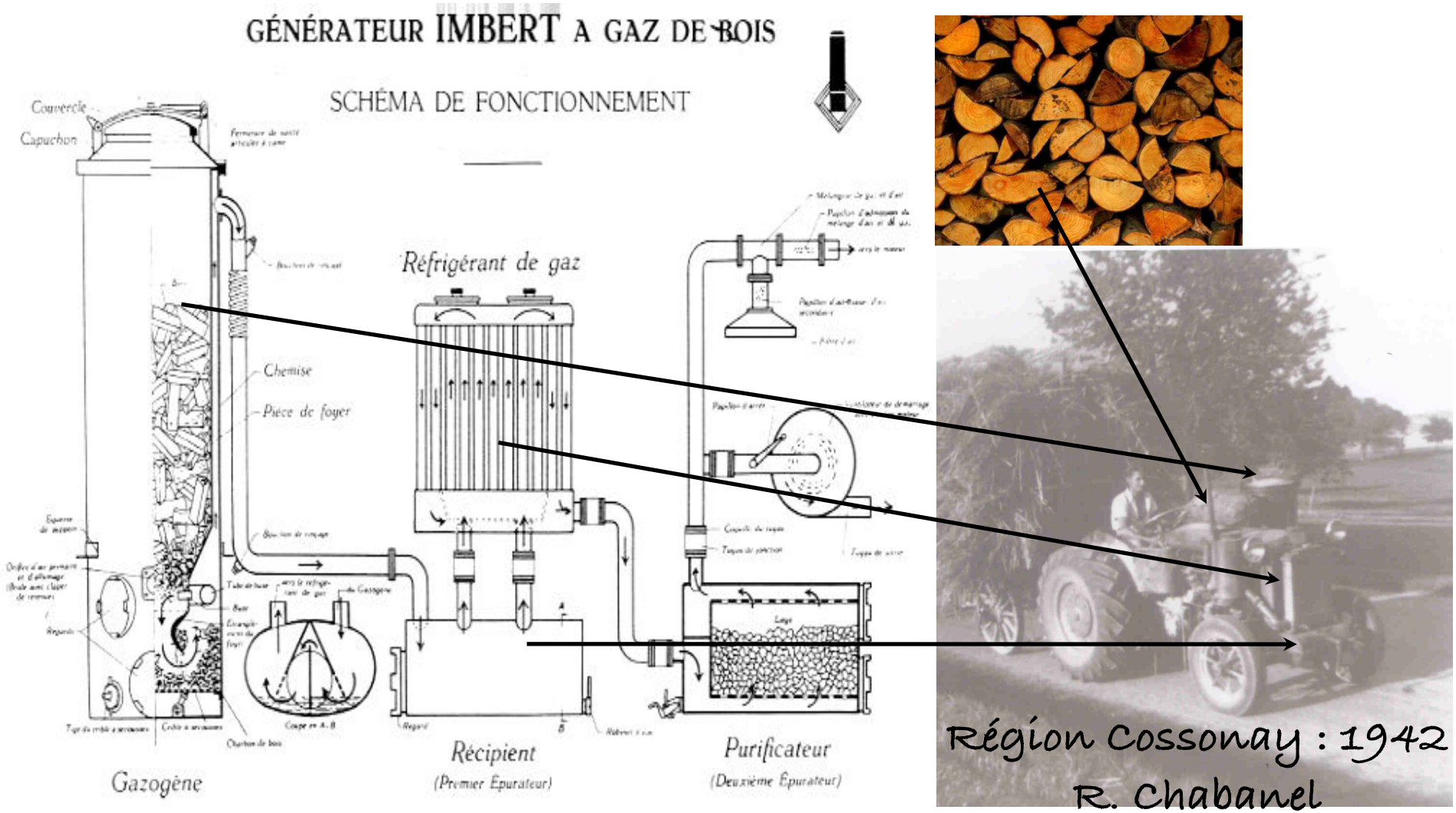

*adapted from Chemical Engineering 10 (2006)*

# Thermochemical biomass conversion

## Process principles: gasification vs. pyrolysis



# Gasification & Fuel



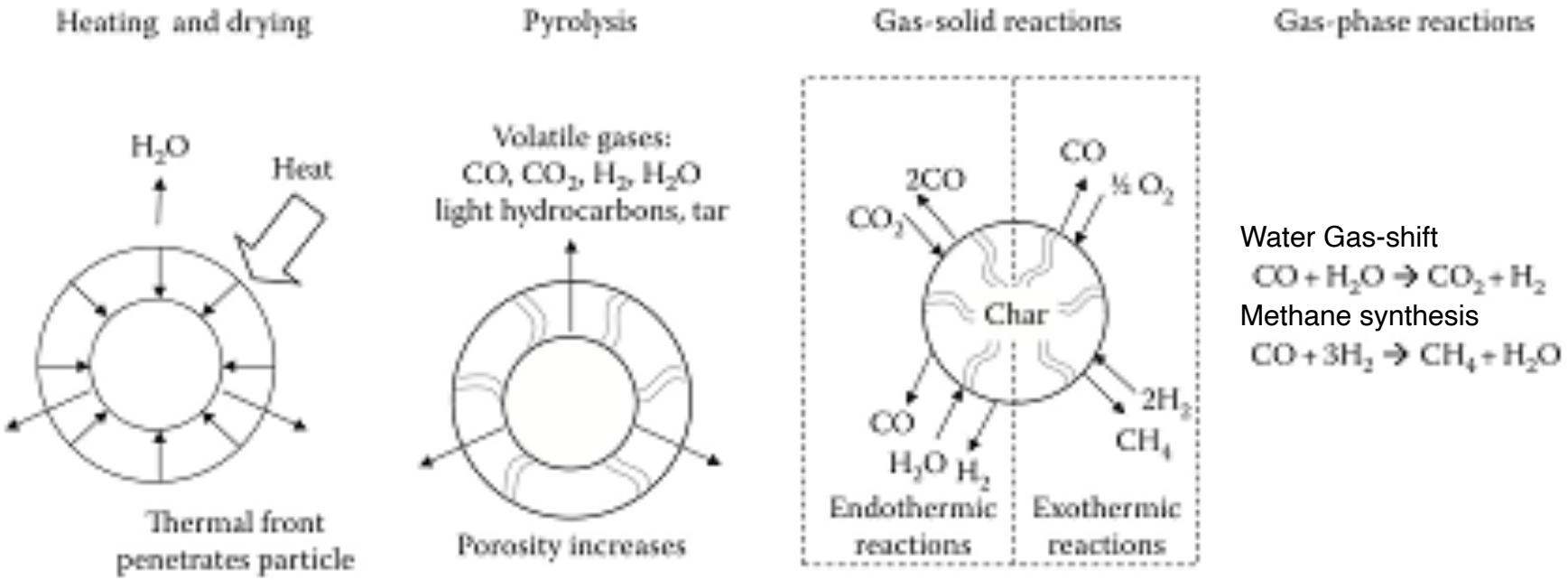
# Gasification



endothermic

$CH_{1.5}O_{0.67} + 0.33\ H_2O \rightarrow CO + 1.08\ H_2$ ($\Delta H$=101 kJ/mol (700-900°C, 1 atm))

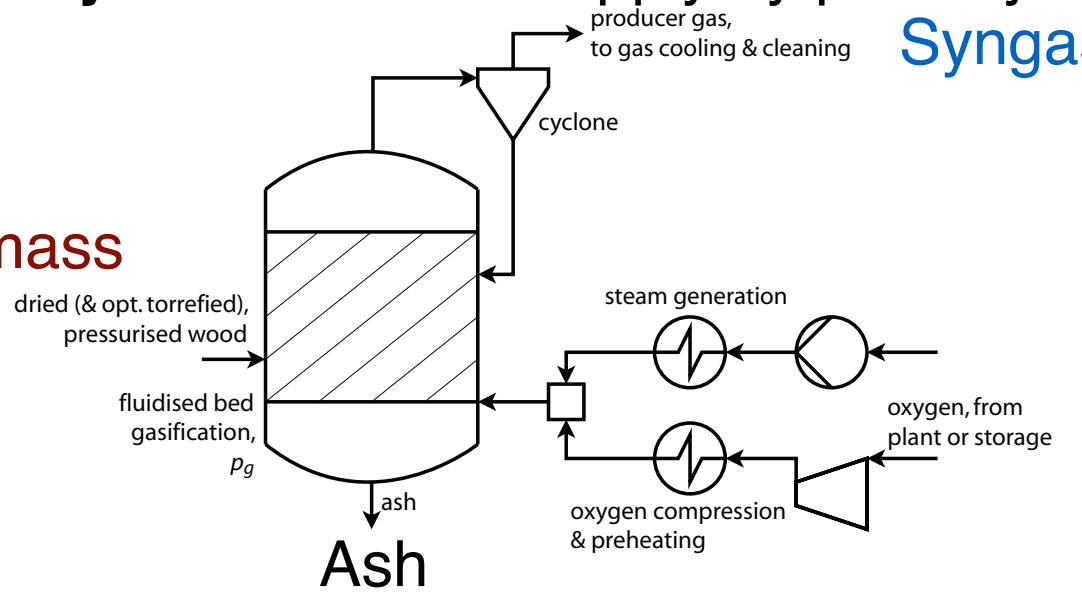
wood steam syngas
(gasifying agent)




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 technologies

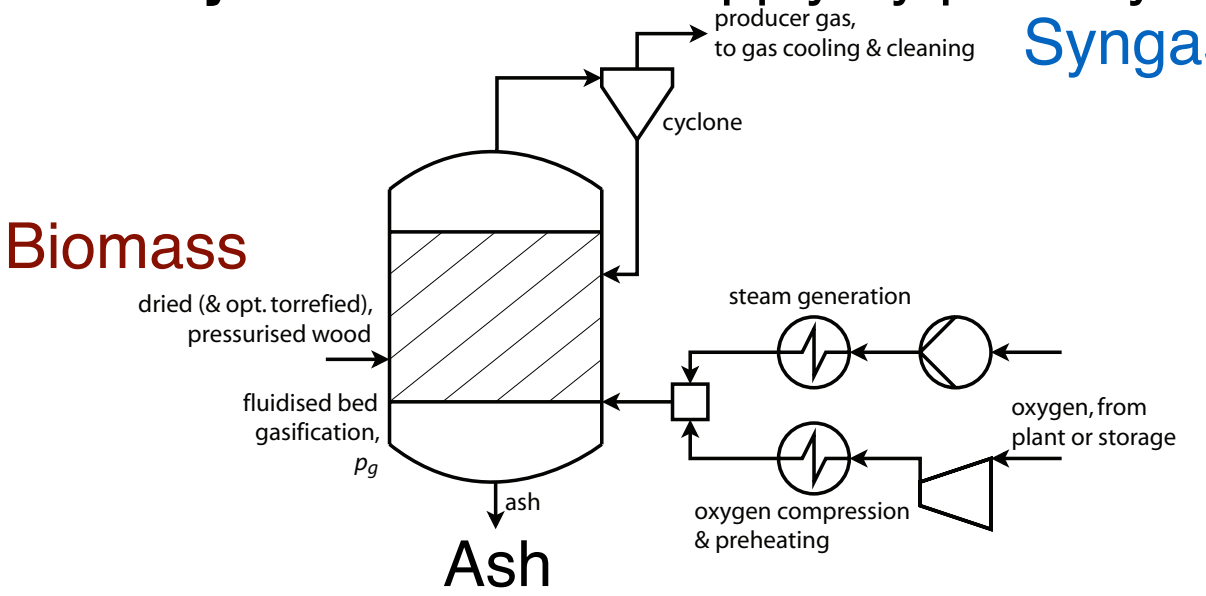
**Directly heated** : heat supply by partially oxidising the biomass




Gasifying agent + oxidant
air / oxygen / steam

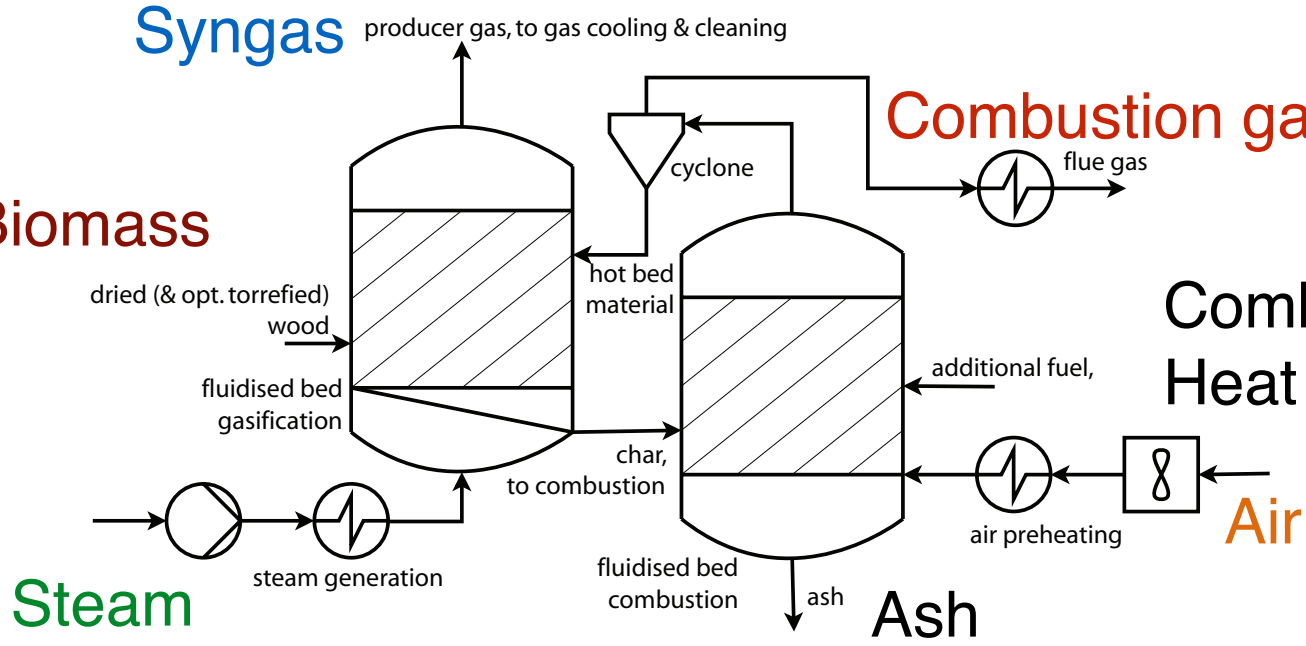
# Gasification technologies

**Directly heated** : heat supply by partially oxidising the biomass




Gasifying agent + oxidant
air / oxygen / steam

**Indirectly heated** : heat supply by burning part of the biomass in a separate boiler

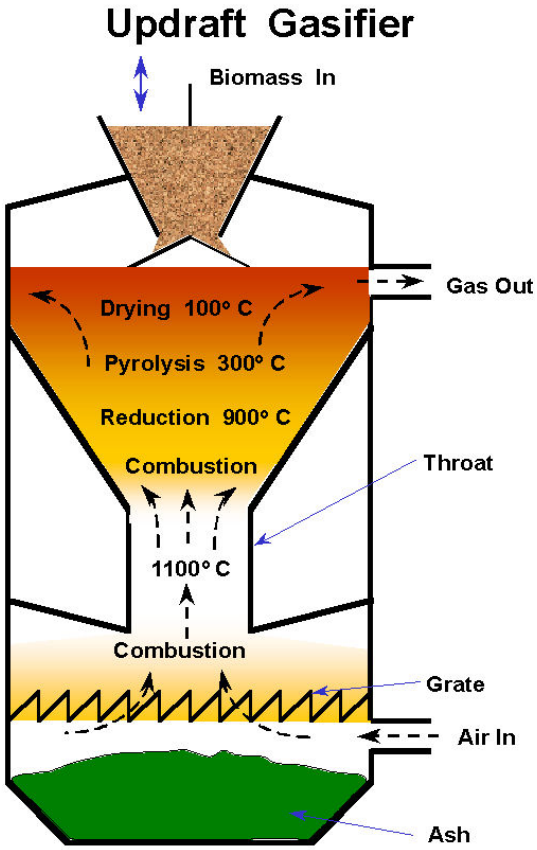


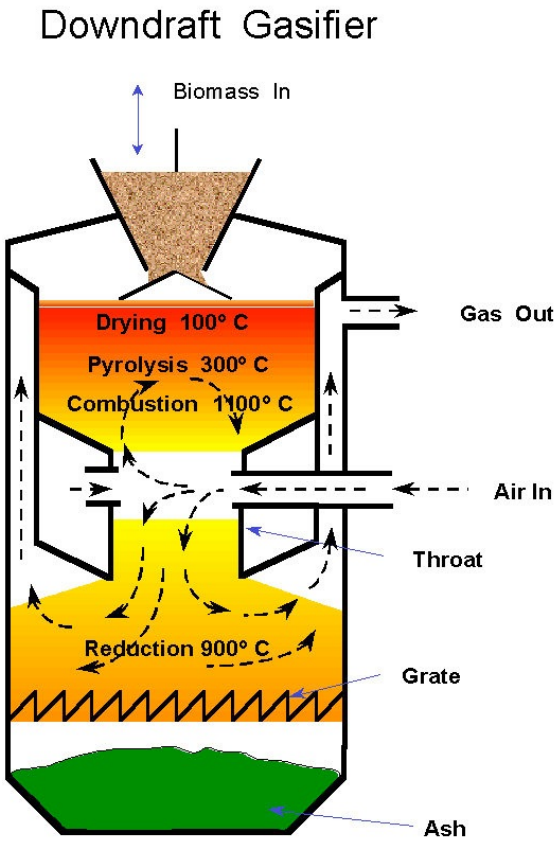

Combustion of char and tars
Heat transfer by fluidised bed

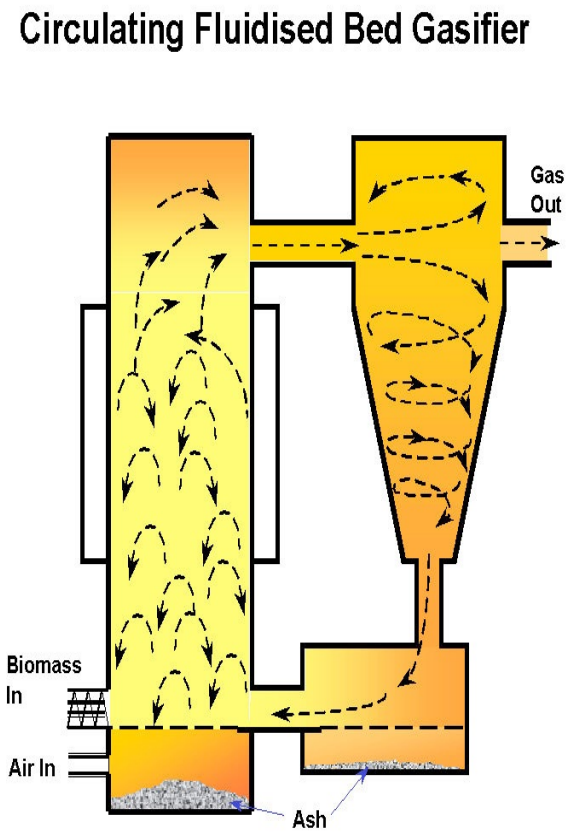
# Different gasifiers arrangement



## Solid - Fluid dynamics is important



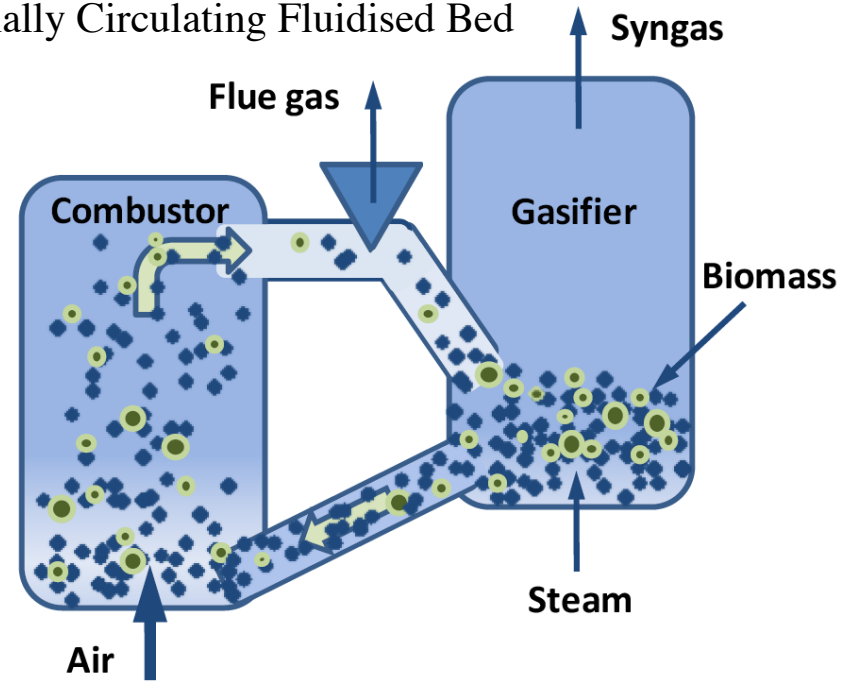




## Heat is supplied by partial oxidation of the biomass

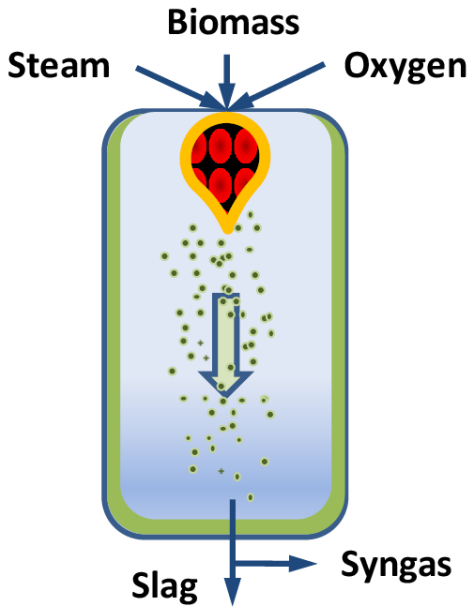
References: MIT open courseware:William H. Green Sustainable Energy November 16, 2010
Capucine Dupont, LTB CEA Grenoble
www.springvale.biz/course%20notes/week11%20Biomass%20wood%20combustion1/week11.htm

# Types of gasifiers
# Comparing operating conditions

FICFB
Fast Internally Circulating Fluidised Bed




Entrained Flow



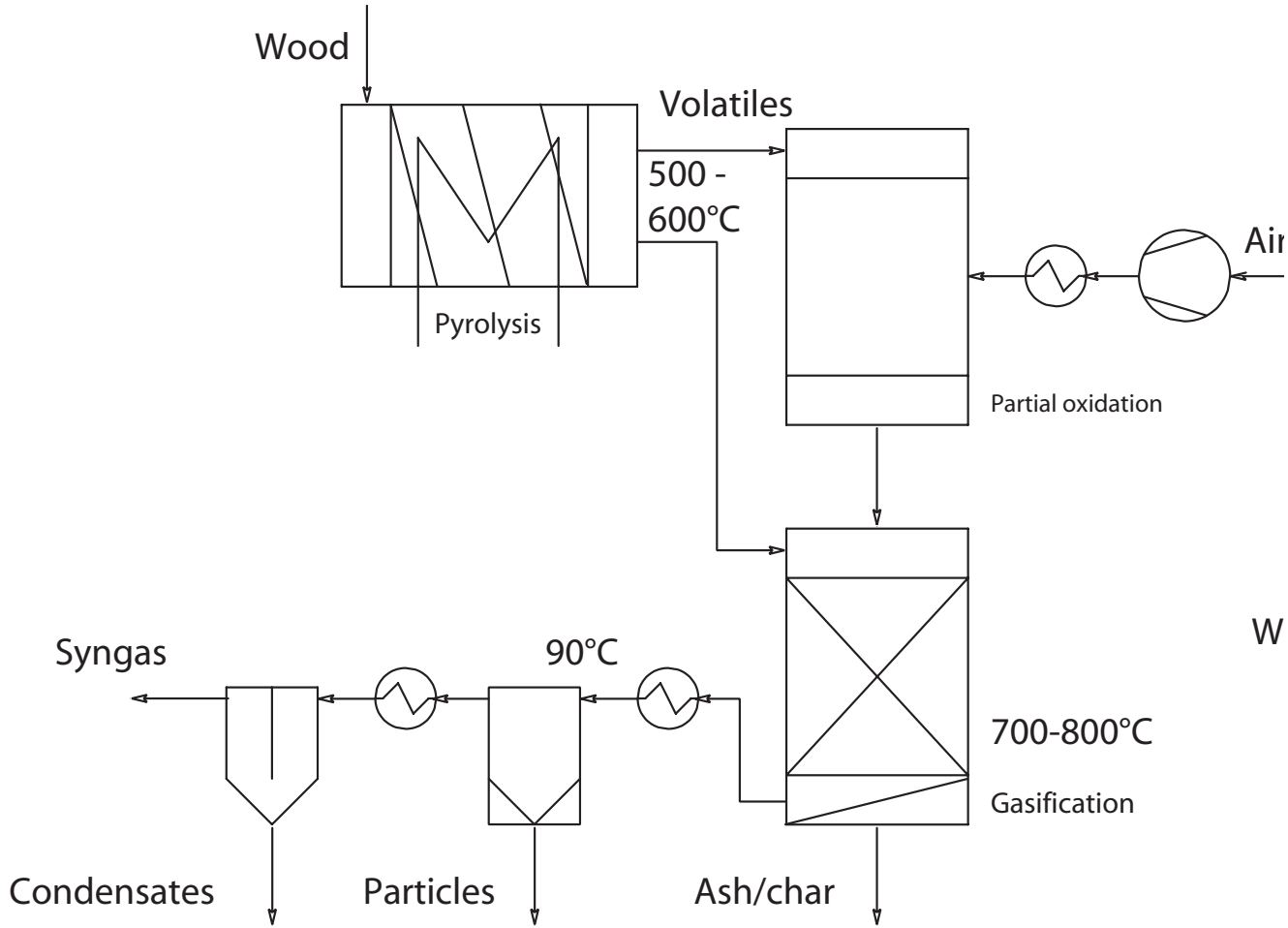

| | | |
|---|---|---|
| Temperature | 800-1000 °C | 1200-1500 °C |
| Pressure | 1-4 bar | 30-80 bar |
| Gas residence time | 10 s | seconds |
| Solid residence time | several minutes | seconds |
| Particle size | 50-150 mm[a] | < 0.1 mm |
| Gasification agent | steam | steam/$O_2$ |

E. Peduzzi : PhD Thesis EPFL, 2015

# Viking gasifiers



- Two stages gasification



# Gas composition modeling



**Table 2 – Gasification and methanation reactions.**

| Interaction | Name | Reaction | | $\Delta\tilde{h}_r^0$ |
|---|---|---|---|---|
| Solid–gas | Hydrogenating gasification | $C(s) + 2H_2 \rightleftharpoons CH_4$ | (3) | −75 kJ/mol |
| | Boudouard equilibrium | $C(s) + CO_2 \rightleftharpoons 2CO$ | (4) | 173 kJ/mol |
| Gas–gas | Methane synthesis | $CO + 3H_2 \rightleftharpoons CH_4 + H_2O$ | (5) | −206 kJ/mol |
| | Ethene reforming | $C_2H_4 + 2H_2O \rightleftharpoons 2CO + 4H_2$ | (6) | 210 kJ/mol |
| | Water–gas shift equilibrium | $CO + H_2O \rightleftharpoons CO_2 + H_2$ | (7) | −41 kJ/mol |

# Equilibrium model

$$\widehat{K}_p = K_p\left(T_g + \Delta T_{eq}\right) \tag{14}$$

$$K_p(T) = \exp\left(\frac{\sum_j n_j \tilde{g}_j^0(T) - \sum_i n_i \tilde{g}_i^0(T)}{RT}\right) \tag{15}$$

$$\widehat{K}_p = \frac{\prod_j p_j^{n_j}}{\prod_i p_i^{n_i}} \tag{16}$$

**Table 4 – Reconciliation of the producer gas compositions at nominal $T_g$ and $p_g = 1$ bar (Data/Calculation [%vol]).**

| Gasifier | Indirectly heated [66] | Directly heated [29] | Directly heated ($O_2$) |
|---|---|---|---|
| $T_g$ | 850 °C | 800 °C | 800 °C |
| $C_2H_4$ | 1.8/1.9 | 2.0/1.9 | –/4.5 |
| $CH_4$ | 8.8/9.6 | 4.2/4.0 | –/9.5 |
| $H_2$ | 37.3/38.5 | 14.8/14.7 | –/25.8 |
| CO | 29.4/27.4 | 15.4/16.0 | –/32.3 |
| $CO_2$ | 16.2/15.8 | 15.0/14.7 | –/24.0 |
| $N_2$ | -[a]/2.9 | 39.6/40.3 | –/0.1 |
| $H_2O$ | 3.6/3.9 | –/8.4 | –/3.8 |
| $\Delta h^0$ [MJ·Nm$^{-3}$] | 12.0/12.2 | 6.2/6.2 | –/12.9 |
| *SN* [-] | 0.24/0.26 | 0.13/0.13 | –/0.13 |

a Although no nitrogen is introduced by the gasification agent, some $N_2$ is used for inertisation of the raw material, which prohibits to attain the criterion on the Wobbe Index at the process outlet. In the remainder of this work, a cut-down to 0.5%vol of the dry gas by inertisation with $CO_2$ is assumed feasible.

**Table 5 – Reconciled gasification model parameters.**

| Gasifier | Indirectly heated | Directly heated |
|---|---|---|
| $\Delta T_{eq,(3)}$ | −280 °C | −280 °C |
| $\Delta T_{eq,(7)}$ | −112 °C | −112 °C |
| $k_{C_2/C_1}$ | 0.205 | 0.476 |
| $\varepsilon_{cc}$ | 90.3% | 93.0% |

# Gas composition as a function of the gasifier type



- Composition depends on gasifying agent

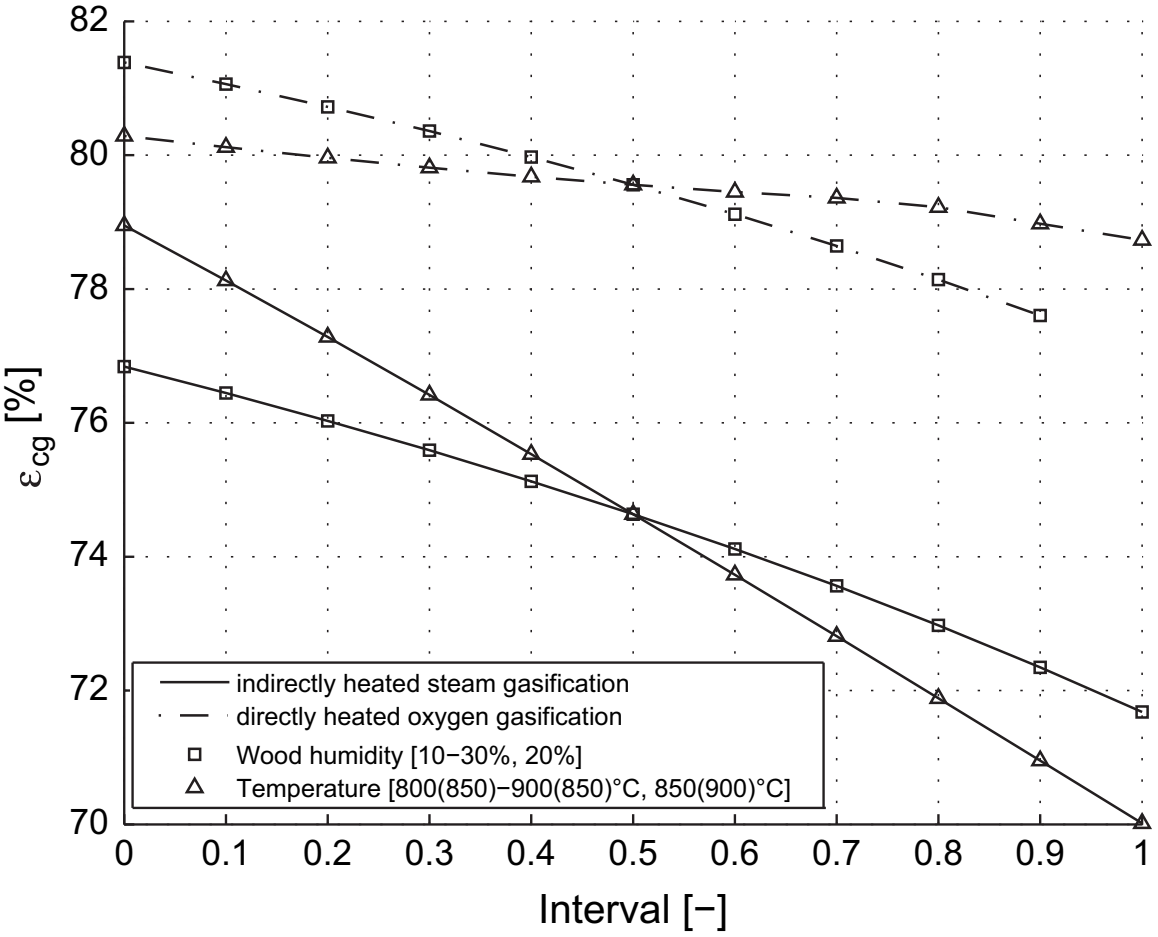
| Reactor (*n* iterations) | Units | $O_2$ gasification (15,000) | | Air gasification (15,000) | | $H_2O$ gasification (15,000) | |
|---|---|---|---|---|---|---|---|
| Tar | mg/N $m^3$ | 5189 | 33,891 | 15 | 382 | 5354 | 86,034 |
| $N_2$ | % | 0.2 | 0.3 | 47.7 | 59.6 | 0.2 | 0.2 |
| $H_2$ | % | 11.5 | 13.3 | 10.7 | 7.5 | 20.1 | 14.2 |
| $CO_2$ | % | 49.3 | 59.5 | 18.9 | 21.2 | 31.2 | 38.2 |
| CO | % | 14.6 | 9.8 | 13.8 | 5.8 | 16.8 | 9.4 |
| $CH_4$ | % | 11.5 | 10.4 | 6.1 | 4.4 | 17.3 | 17.1 |
| Other HC | % | 12.8 | 5.6 | 2.7 | 1.0 | 14.3 | 18.3 |
| $NH_3$ | % | 5.44E−03 | 3.18E−02 | 5.91E−02 | 4.63E−01 | 4.38E−02 | 4.56E−02 |
| Furfural | % | 2.58E−02 | 7.19E−01 | 8.41E−05 | 6.52E−03 | 6.46E−03 | 9.03E−02 |
| Phenol | % | 1.21E−01 | 3.99E−01 | 2.41E−04 | 1.55E−03 | 1.40E−01 | 1.81E+00 |
| Naphthalene | % | 1.28E−02 | 1.62E−02 | 1.69E−07 | 2.14E−06 | 1.34E−02 | 6.80E−01 |
| Pyridine | % | 4.17E−03 | 1.83E−02 | 1.06E−04 | 2.94E−03 | 6.54E−03 | 6.58E−02 |
| Char | % | 5 | 23 | 6 | 24 | 10 | 10 |

D. Brown et al. / Applied Thermal Engineering 29 (2009) 2137–2152

# Effciency of gasifiers : cold gas efficiency



- Efficiency depends on the type of gasification




$$\varepsilon_{cg} = \frac{\Delta h^0_{gas} \dot{m}^-_{gas}}{\Delta h^0_{wood} \dot{m}^+_{wood}}$$

**Fig. 4 – Cold gas efficiencies in parameter domain.**

# Gas composition as a function of the gasifier type



- Composition depends on gasifying agent
- Composition depends on gasifier technology
- Composition depends on operating composition

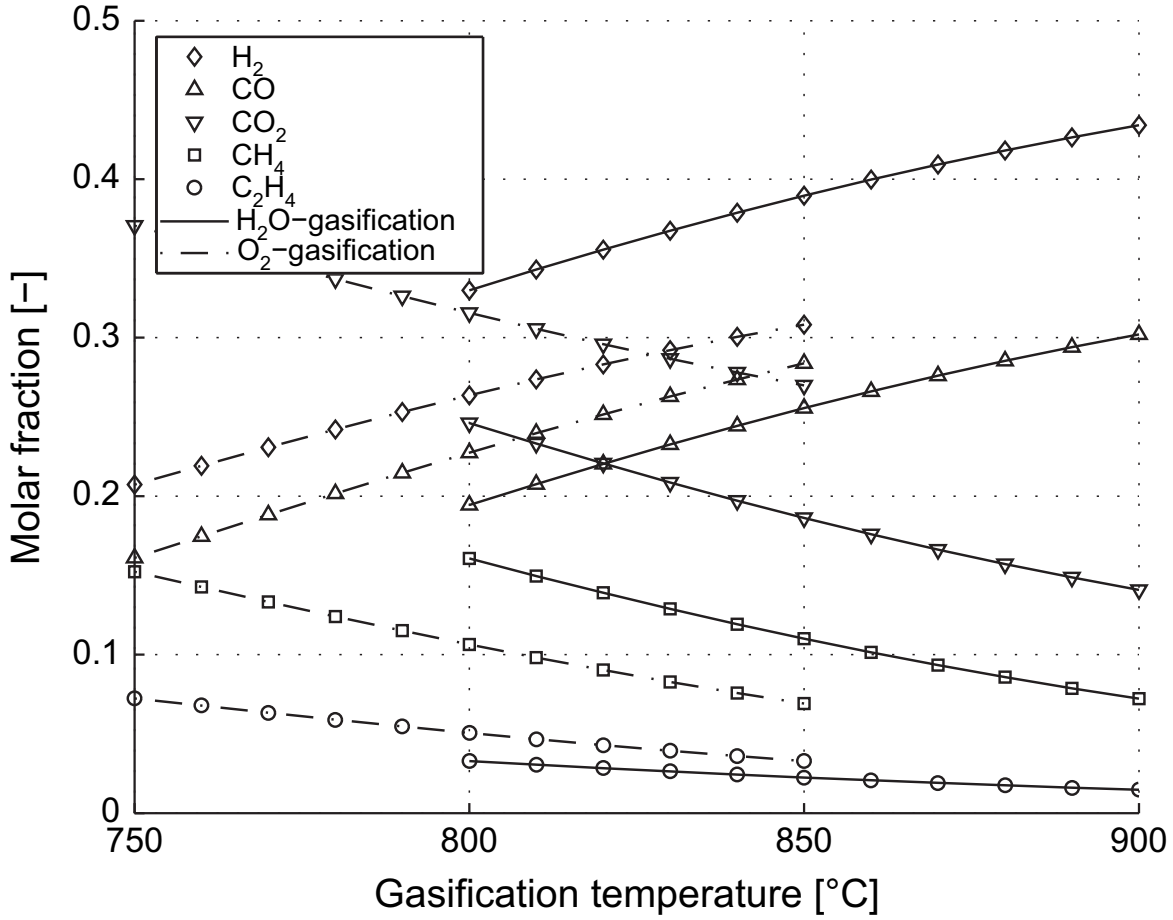


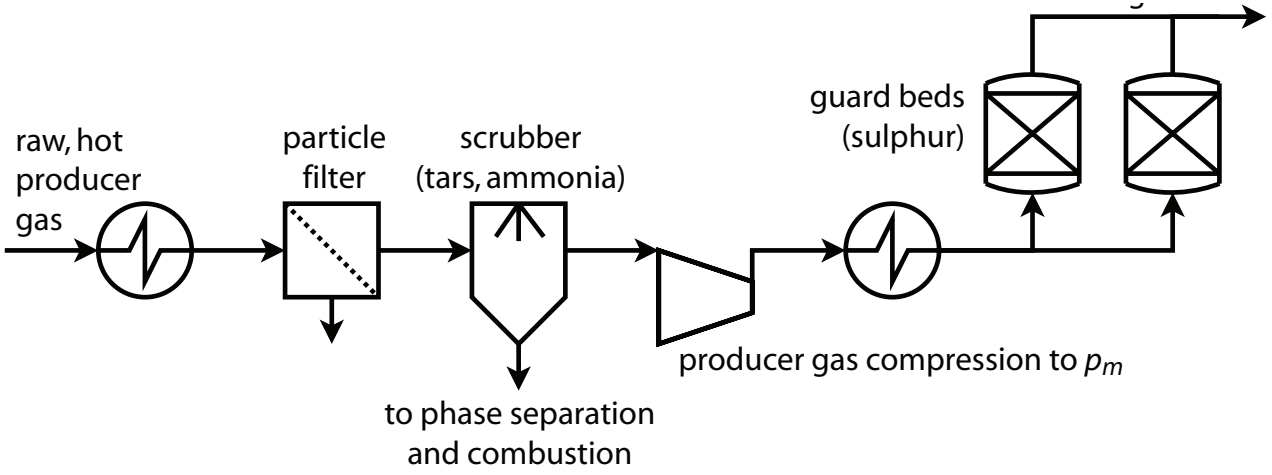

**Fig. 3 – Molar compositions of the dry gas from gasification.**

biomass and bioenergy 33 (2009) 1587–1604

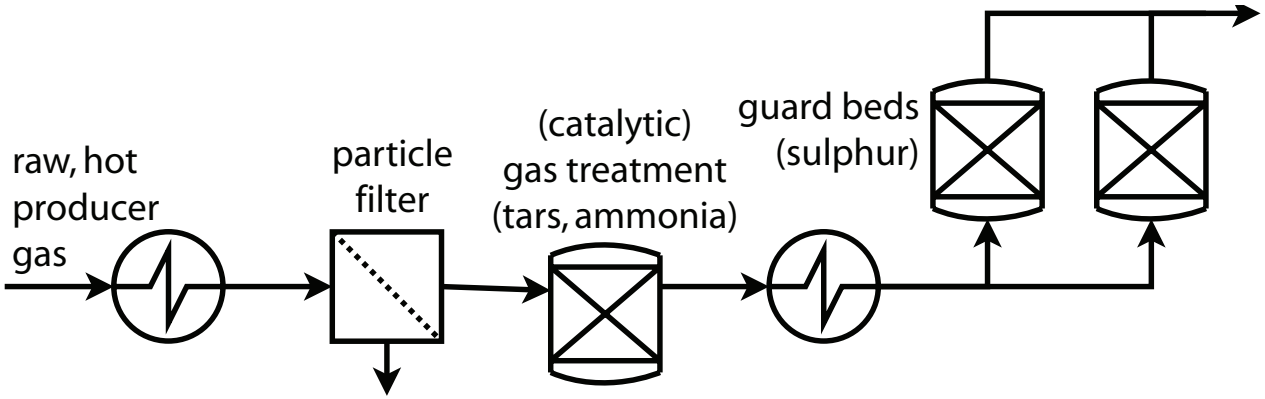
# Gas cleaning



- Remove the impurities (inc. H2S, $S_2$)



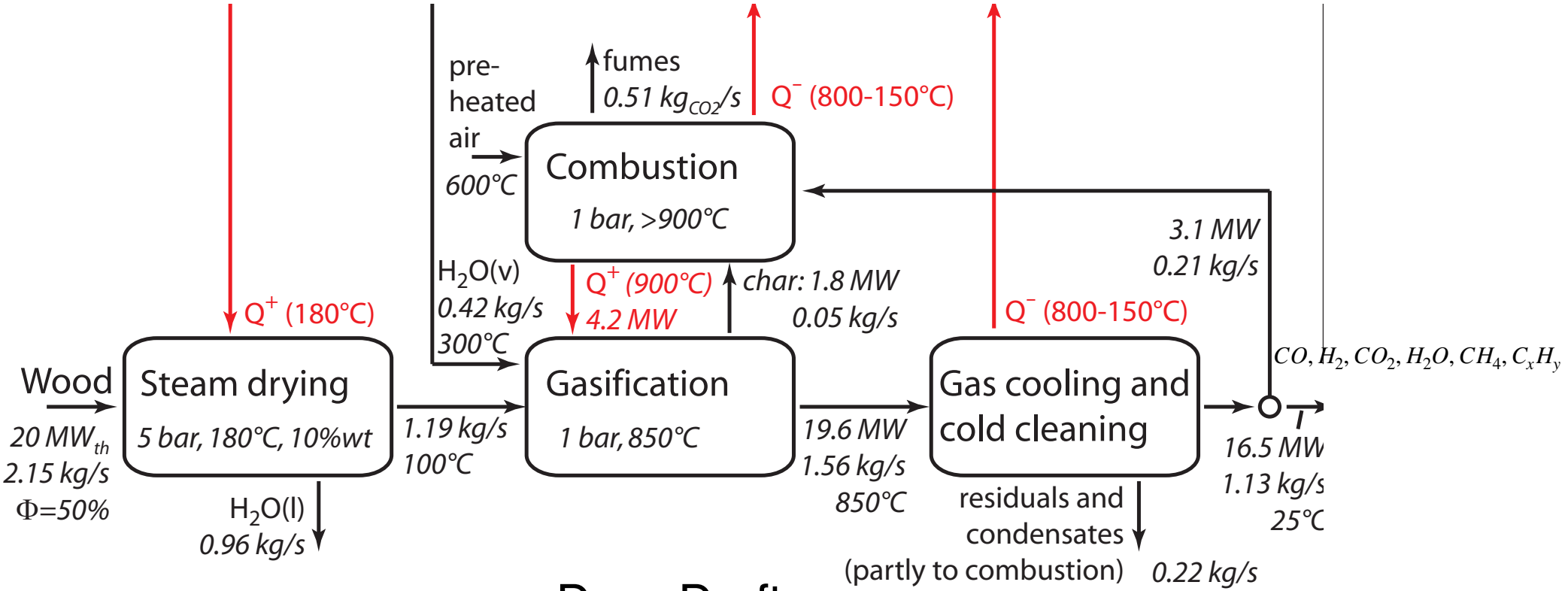

(a) Cold gas cleaning.




(b) Hot gas cleaning.

# The gasification system

## SOLID -> SYNGAS




DownDraft
Entrained flow
Indirectly heated
Multi-stage

# Conclusion : gasification



- CO and H2 are produced (carry the LHV : eff : 80%)
- Gasifying Agent
  - O2
  - Air
  - Steam
- Heat by oxidation of the part of the biomass
  - Heating : direct or indirect
  - Fluidised bed material (can be catalytic)
- Design, operating conditions and residence time are critical
  - Solid-Gas : drying - pyrolysis - gas release
  - Gas phase : reforming reactions
- Ash separation
- Gas cleaning
- Heat recovery