# Biomass:
# Wood conversion (and energy crops)

# Learning objectives in this section

- Distinguish **pyrolysis** / gasification / combustion of wood
- Know different (wood) gasification concepts and their basic characteristics
- Know wood **impurities**, and cleaning processes
- Know different uses of wood in **power plants**, their power **sizes** and electrical **efficiencies**

# Uses of wood

- energy use:
  - ca. 50% of forest ‘waste’
  - mostly in direct combustion for heat
- *other* uses:
  - construction, furniture, packaging
  - paper production
  - wood chemistry (*xylochemistry*): $CH_4$, alcohols, pharmaceuticals
  - annex products: cork, resin, rubber, tanins,..

# Biomass roadmap: energy uses of wood

## Source

- Solid (wood, straw)
- Wet (waste, manure)
- Sugar/starch
- Oil crops

## Process

- Combustion
- Gasification
- Pyrolysis
- Methanation
- Fermentation
- Extraction + esterification

## Product

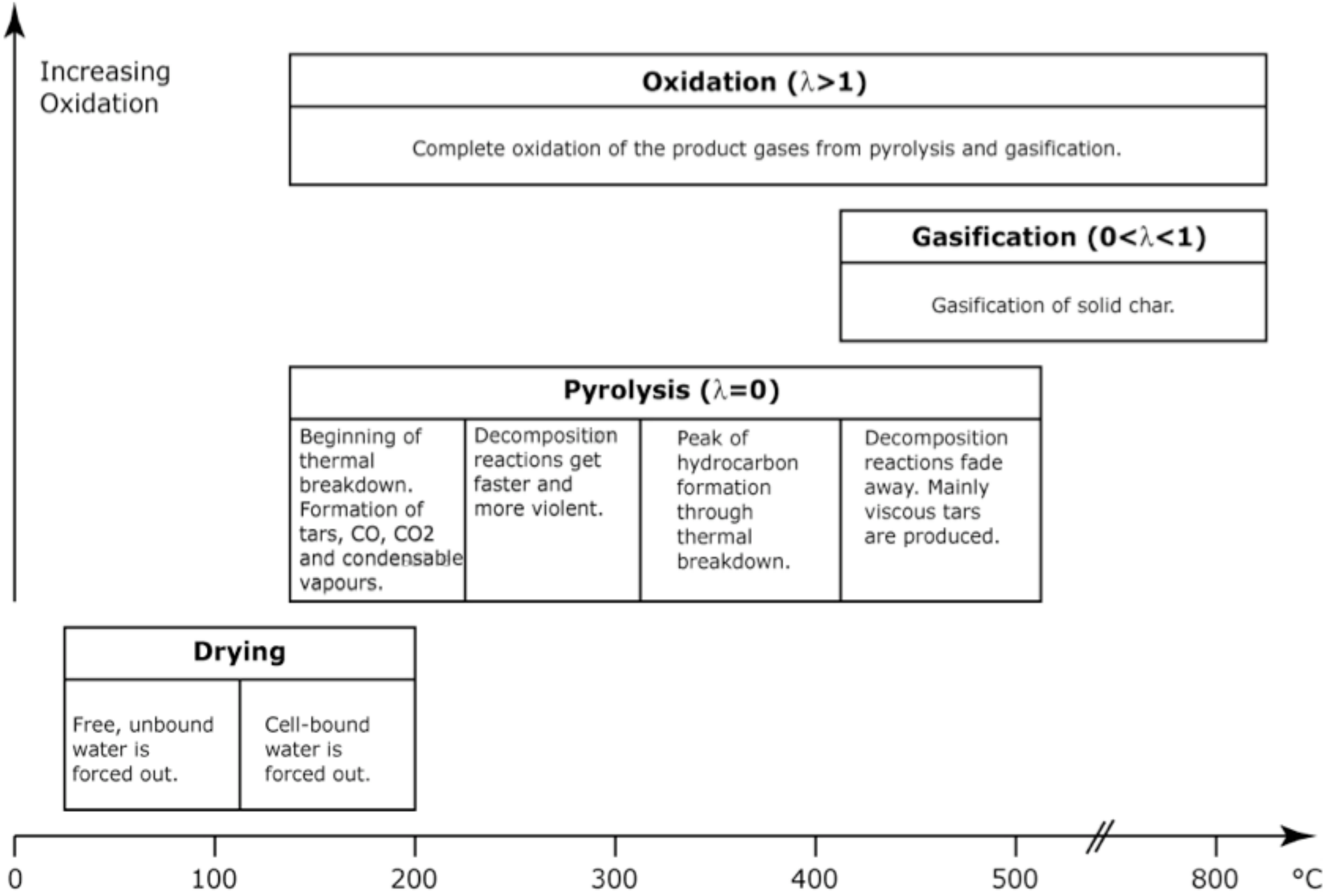
- Heat
- Woodgas
- Woodoil
- Biogas
- Bioethanol
- Biodiesel

## Service

- Heat / CHP
- Electricity
- (Transport) Fuels
- Chemicals

# Combustion / Gasification / Pyrolysis

**→ *distinguished by the amount of oxygen addition (λ):***



# Thermochemical conversion :

| Process | T(°C) | $\lambda$ | Product |
|---|---|---|---|
| Pyrolysis | 400-700 | 0 | combustible gas + liquid + solid |
| Gasification | 700-900 | Air: 0.2 to 0.5<br>Steam: 0.4 to 3 | Low LHV gas<br>High LHV gas<br>Incombustible solid |
| Combustion | 800-1300 | $\geq 1$ | Incombustibles (gas, solid) |

# Direct wood combustion

- theoretical air-factor for dry wood : 6 kg air / kg wood;
  in practice: **8.4 kg air** / kg wood
- combustion temperature:
  - open chimney **600°C**
  - wood pellet firing **1300°C**
- combustion efficiency depends on:
  - combustion degree, wood humidity, air factor, insulation losses, exhaust fumes temperature
  - for dry wood : **70-80% efficient**; for solid 'wastes': only 50% efficient
- wood **drying** may consume up to **10%** of the primary energy
- **pelletizing** (extrusion) requires **2%** of primary energy
  - 50-70 $kWh_{el}$ (180-250 MJ) for the extrusion of 1 tonne compacted wood

# The combustion process in detail:

- **at low T** (200°C): **aromatic** oils set free (high LHV, volatile)
  → large gas flames
- **at medium T** (300-400°C) : **lignocellulose** decomposes to volatiles → gas flames
- **at high T** (500-600°C): solid **carbon** residues burn by surface oxidation → no flames, but incandescence
- softwood contains more lignine and aromatic oils:
  → hence higher LHV, easier ignition, large brilliant flames
- even in Switzerland, wood firing is responsible for the highest concentration of atmospheric fine **dust particles** in winter (*more than from road traffic!*); half of the emissions occur during the first 10 minutes (ignition = incomplete combustion; cf. the cold-start of engines)

# Wood : heating value

- cellulose/hemicellulose : **17.46 MJ/kg** (45 wt% carbon)
- lignine : **26.63 MJ/kg** (60 wt% carbon)

$$LHV_{dry} = 17.46 * C + 26.63 * (1 - C) \pm 0.4 \ MJ / kg$$

with C = cellulose+hemicellulose, 1-C = lignine content

- hardwood (oak, beech, maple, teak, walnut, poplar, birch):
  22% lignine, 500 kg/m$^3$, 19.5 MJ/kg, slow growth, dark color, loose leaves
- softwood (all pinewoods and resinous trees, cedar, larch):
  29% lignine, 300 kg/m$^3$, 20.1 MJ/kg, fast growth, light color, evergreen
- aromatics (only 1 wt% in wood) have highest LHV of **35 MJ/kg**

# Humidity

- *'dry'* wood : between 5% (@30°C, 20% RH) and 27% (@0°C, 95% RH) water content by weight

  '*green*' wood: 25-65% humidity

- *'captive'* humidity: $H_2O$ retained *within* the fibres; this water is removed **irreversibly** when dried (and the fibres contract)

  '*free*' humidity: $H_2O$ retained *between* the fibres; this depends on the ambient conditions (**reversible** uptake and release of water)

- humidity reduces the LHV per kg:
  1. due to the density loss when $H_2O$ replaces wood
  2. due to the evaporation heat required (2.44 MJ/kg $H_2O$)

→ for typical dry wood (15%-25%) : 14-16 MJ/kg

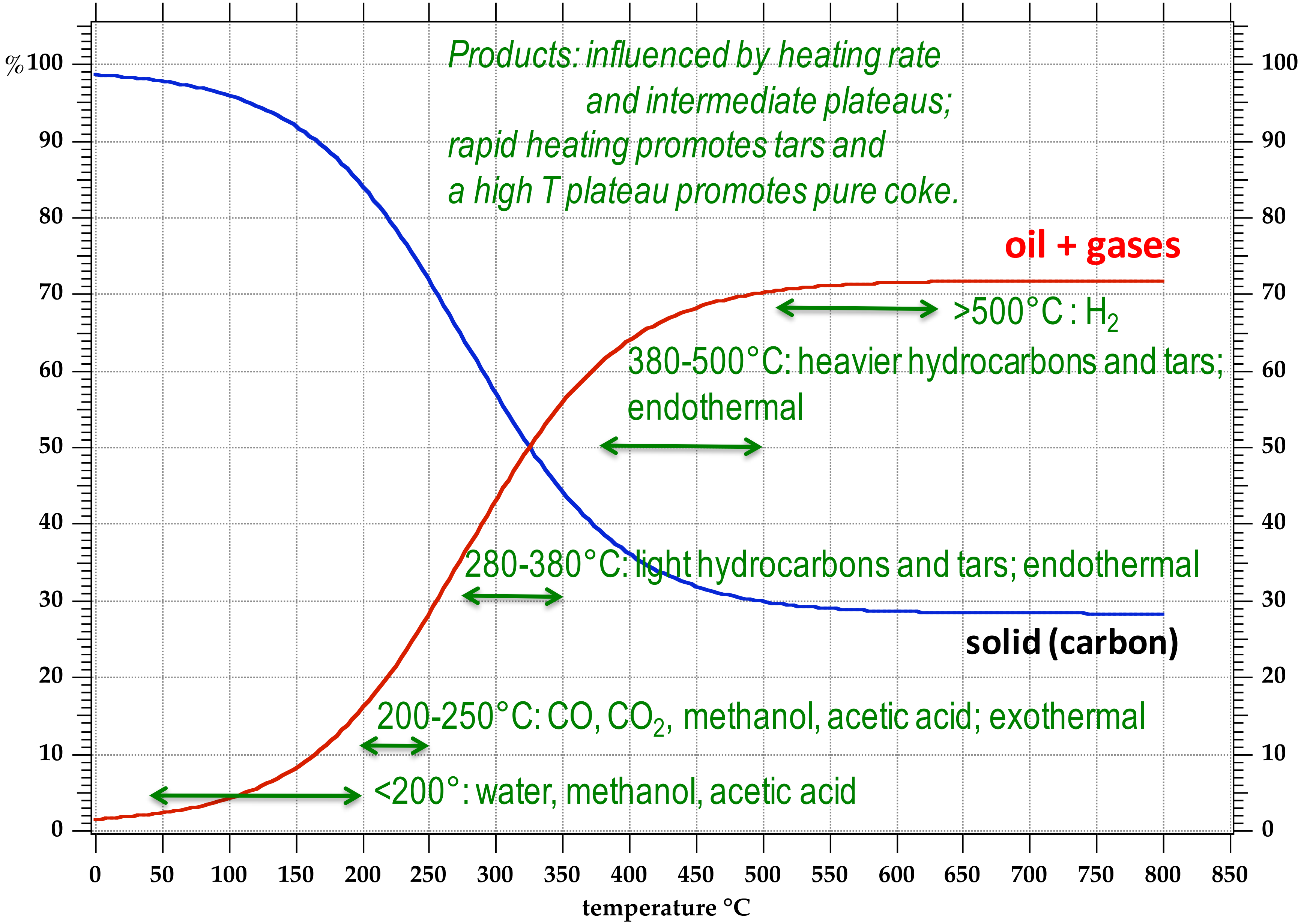
$$LHV_{humid} = LHV_{dry} * (1 - 1.14 * W)$$

*W = water content in weight fraction*

# Pyrolysis (= “wood distillation”)

- 1000 kg dry wood generates:
  - 200 kg gas  CO, $H_2$, $CO_2$, $CH_4$
  - 360 kg pyrolysis ‘oil’
    - 12 kg acetic acid, 30 kg methanol, 10 kg acetone, etc.
  - 110 kg ‘tars’ (condensable oxyhydrocarbons)
    - 65 kg creosol oil (30 kg cresoles/gaiacoles, 3 kg phenol, 32 kg others like methanol (‘wood alcohol’), aromatic essences,…)
    - 10 kg furfural
    - 35 kg wood ‘pitch’ (bottom residue)
  - 330 kg charcoal (90% carbon)

# Pyrolysis products as f(T)

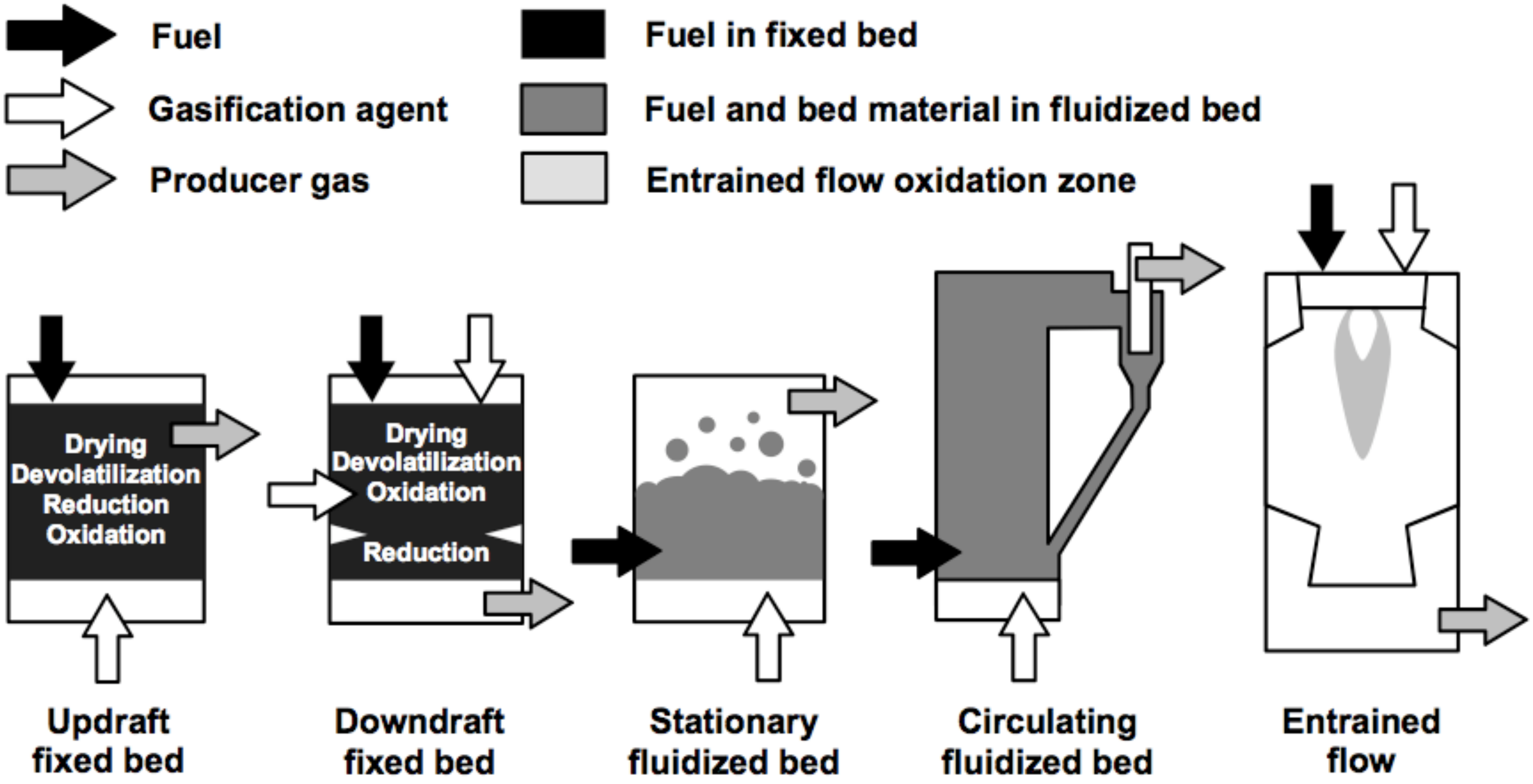


# Pyrolysis energy balance *(exercice)*

- Input:
  - 17 MJ/kg dry wood
  - heat supply (endothermal) : 2.4 MJ
    (=delivered from burning the liberated gases)
- 1 kg dry wood delivers:
  - 150 L of gas with a LHV equal to ⅕ that of natural gas
  - 0.5 kg of liquids with a LHV equal to ¼ that of oil
  - 0.3 kg of charcoal with a LHV equal to that of coal
- Compute the energy balance
  (for the total balance, and for the solids energy (carbon) only)

# Wood (and other solid waste) gasification concepts

http://www.youtube.com/watch?v=86ihCjTA0NE




*F. Nagel, PhD thesis, PSI (2010)*

# Gasification subprocesses (temperature zones)

| Process | Nature | T-range (°C) | Subproduct |
|---|---|---|---|
| Drying | Endothermal | <200°C | dried biomass |
| Devolatilisation (= thermal decomposition without oxidant) | Endothermal | 200-600°C | $H_2$, CO, $CO_2$, $CH_4$, $C_xH_y$, tars, charcoal |
| Reducing | Endothermal | 600-1000°C | reforming, shift, methanation reactions |
| Oxidising | Exothermal | 1000-1600°C | $CO_2$, $H_2O$ |

# Classification of gasifier concepts:

1. Reactor type
   - *fixed* bed
   - *fluidised* bed
   - *entrained* flow

2. Heat supply
   - direct
   - indirect

3. Gasification agent
   - air (exo)
   - $O_2$ (exo)
   - steam (endo)

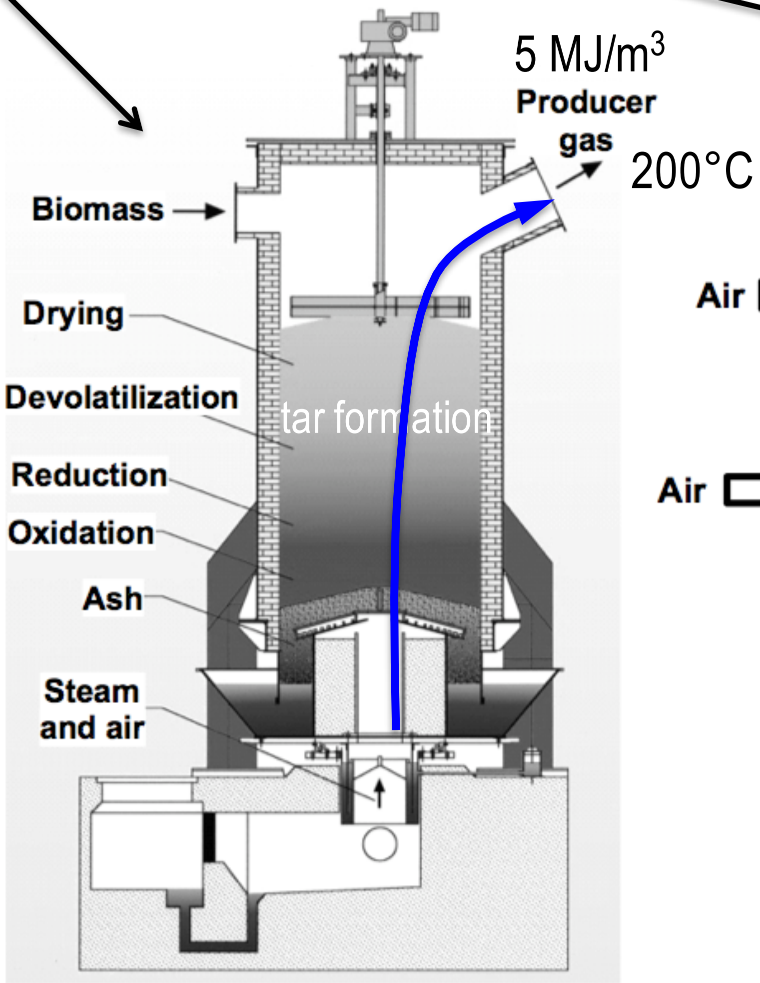
4. Stages
   - single
   - two

http://www.youtube.com/watch?v=GkHKXz3VaFg

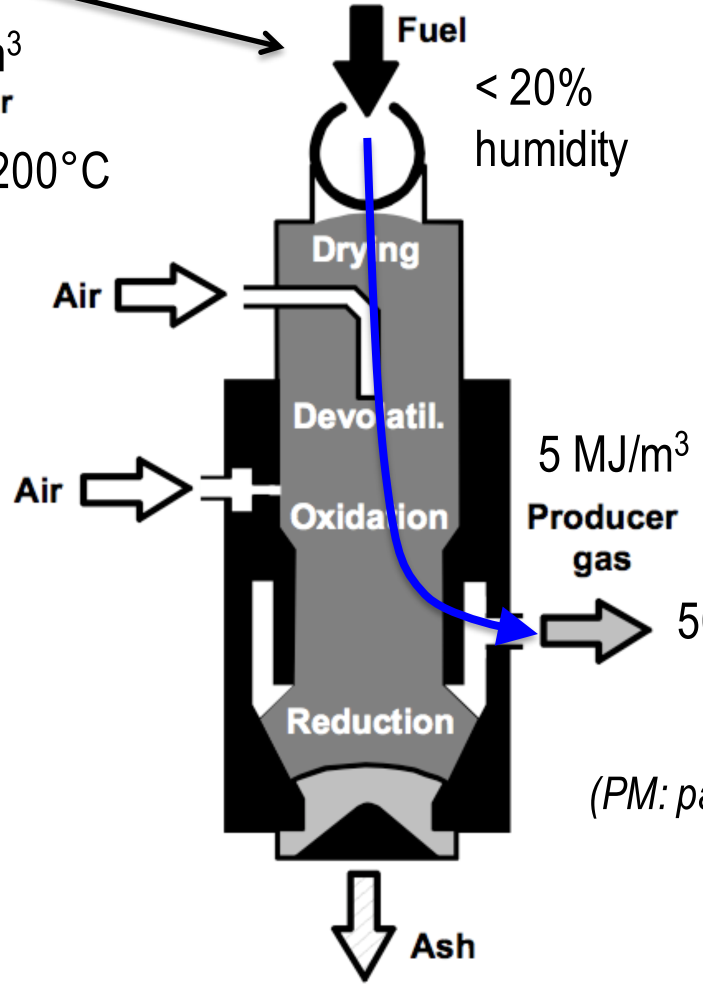
# Updraft / Downdraft (fixed beds)

*F. Nagel, PhD thesis, PSI (2010)*

up to 50% humidity




< 20% humidity




*(PM: particulate matter)*

high tars (150g/m$^3$) – since in low T zone; low PM (since wood inlet top zone acts like a particle filter); scalable to **20 MW$_{th}$**

low tar (< 6g/m$^3$) – all cracked at high T higher PM (no filtering by wood) **2 MW$_{th}$** max (limited heat transfer from the sides for thermal homogeneisation)

# Differences up/down-draft

- **Up**:
  - the upward flow entrains the volatiles (**tars**) through the wood layers in the cold drying stage, where they cannot be decomposed, but the wood retains the particulate matter (**PM**)
  - exit temperature must be high enough to avoid tar condensation
  - robust and scalable

- **Down**:
  - the downward flow entrains the volatiles (**tars**) into the hottest combustion zone where these are cracked to CO and $H_2$
  - limited in power size; more critical thermal management

# Circulating fluidised beds (CFB)

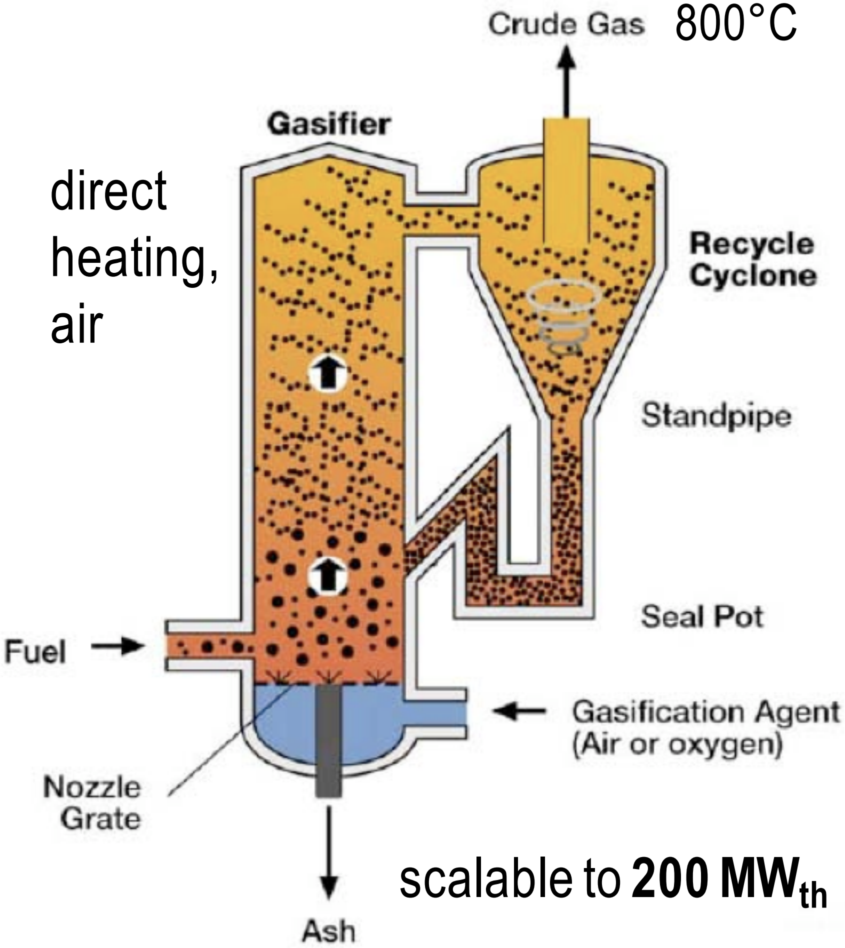
*no distinct temperature zones like for up/down-draft; isothermal due to the circulation*

## CFB

5 MJ/m$^3$

800°C

direct heating, air

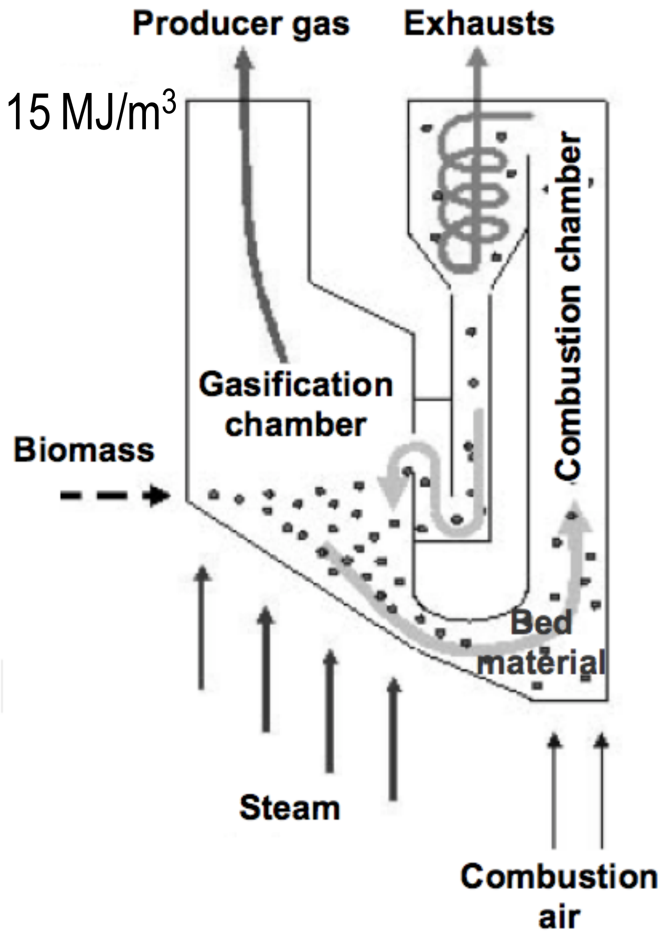



scalable to **200 MW$_{th}$**

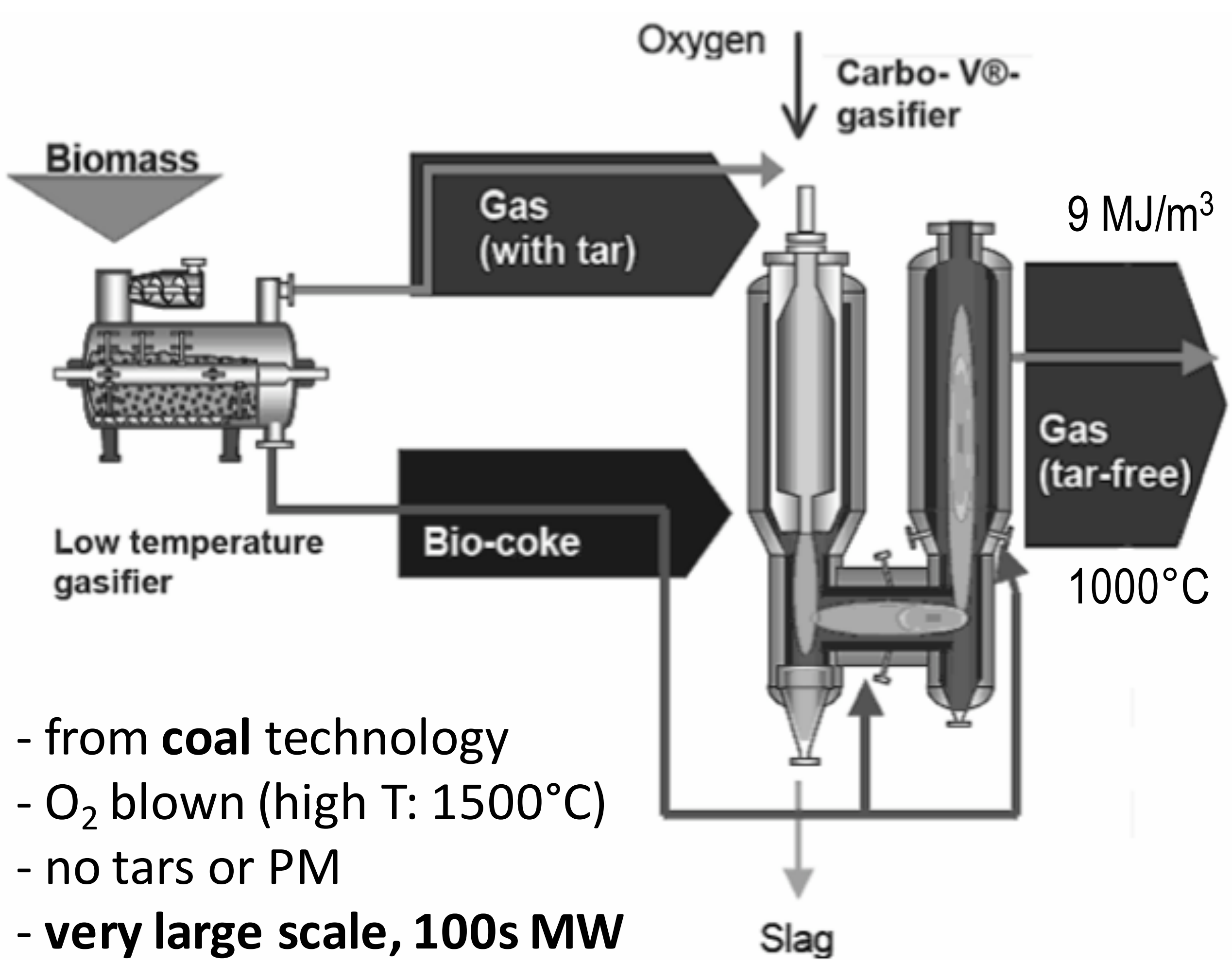
## FICFB (Fast Internally CFB)

15 MJ/m$^3$

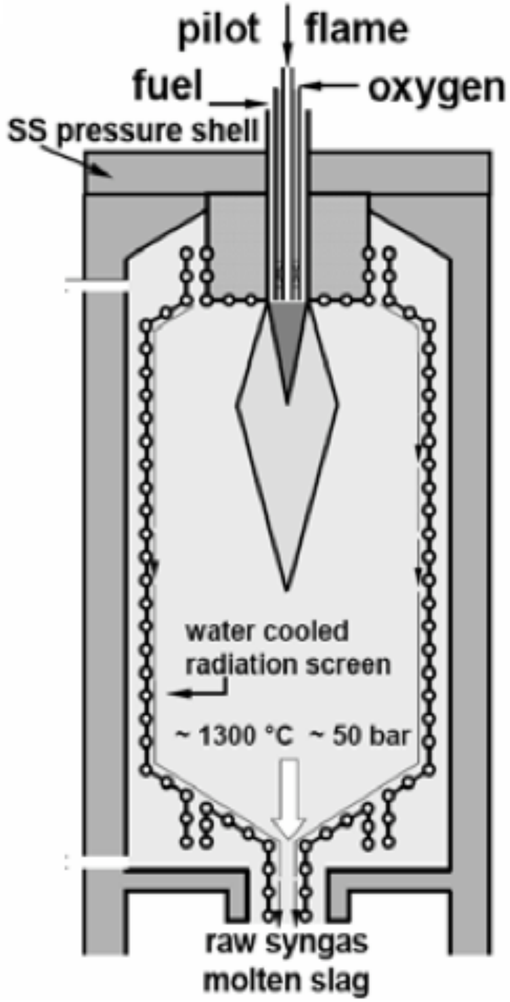
indirect heating, steam



# Entrained flow gasifiers




- from **coal** technology
- $O_2$ blown (high T: 1500°C)
- no tars or PM
- **very large scale, 100s MW**




*F. Nagel, PhD thesis, PSI (2010)*

# Gasification comparison

*F. Nagel, PhD thesis, PSI (2010)*

| | Unit | Updraft | Down-draft | Fluid. Bed | Circul. FB | Entrain. flow |
|---|---|---|---|---|---|---|
| Gasification agent | [-] | Air | Air | Air/$O_2$/ $H_2O$ | $H_2O$ | $O_2$ |
| $H_2$ | [mol-%] | 10-14 | 15-21 | 15-22 | 17-36 | 29-40 |
| CO | | 15-20 | 10-22 | 13-15 | 36-51 | 39-45 |
| $CO_2$ | | 8-10 | 11-13 | 13-15 | 7-15 | 18-20 |
| $CH_4$ | | 2-3 | 1-5 | 2-4 | 0.1-0.6 | 0.05-0.1 |
| $C_2$ | | - | 0.5-2 | - | 1.4-7.5 | - |
| $N_2$ | | 53-65 | 37-63 | 44-57 | 0-39 | 0.1-9 |
| LHV | [MJ/$m_n^3$ (dtf)] | 3.7-5.1 | 4.0-5.6 | 3.6-5.9 | 14.2-18.1 | 8.8-9.3 |
| Gas temperature | [°C] | 75-300 | 500-900 | 800-950 | 800-950 | 800-1000 |
| Cold gas efficiency | [%] | >90 incl. tar | 65-75 | 70-85 | 60-70 | 50-70 |
| Particle load | [g/$m_n^3$ (dtf)] | 0.1-3 | 0.02-8 | 20-100 | 8-100 | - |
| Tar load | | 10-150 | 0.01-6 | 2-50 | 1-20 | 0 |
| Tar signature | [-] | mostly oxygen-ated | aromatic | oxygen-ated and aromatic | oxygen-ated and aromatic | none |
| Alkali phase | | solid | liquid | liquid | liquid | liquid/ gaseous |
| Sulfur signature | | partially organic | mainly inorganic | partially organic | partially organic | inorganic |
| Feed size & geometry | | non-sensitive | homoge-neous | homoge-neous | homoge-neous | Suspen-sion |
| Feed humidity | | <50 % | <20 % | <15 % | <15 % | - |
| Process robustness | | stable | sensitive, bridge building | stable | stable | sensitive, slagging |
| Reactor size | [$MW_{th}$] | 0.1-20 | 0.1-2 | 1-50 | 20-200 | 30-600 |

# **Gasification energy balance (downdraft, air)** *(exercice)*

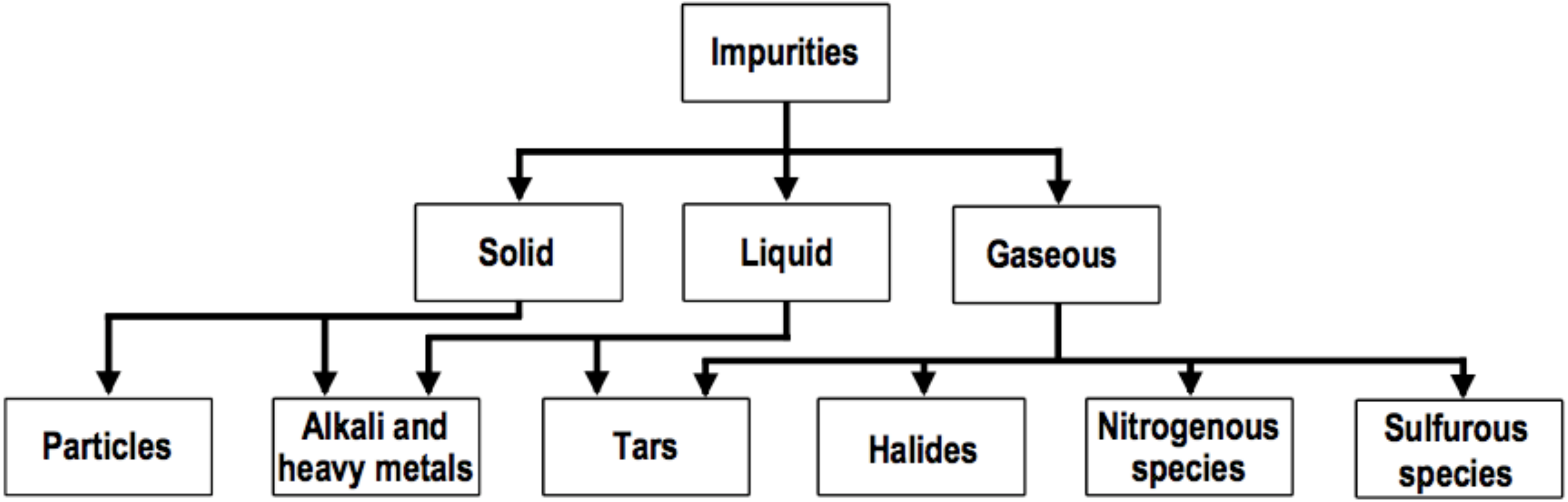
- Input 1 kg dried wood (15wt% residual humidity)
- delivers 2 $m^3$ producer gas of :

  18% $CO$ / 16 % $H_2$ / 2 % $CH_4$ / 14% $CO_2$ / 50% $N_2$

  (LHV: 305 kJ/mole ($CO$); 241 kJ/mole ($H_2$); 800 kJ/mole ($CH_4$))

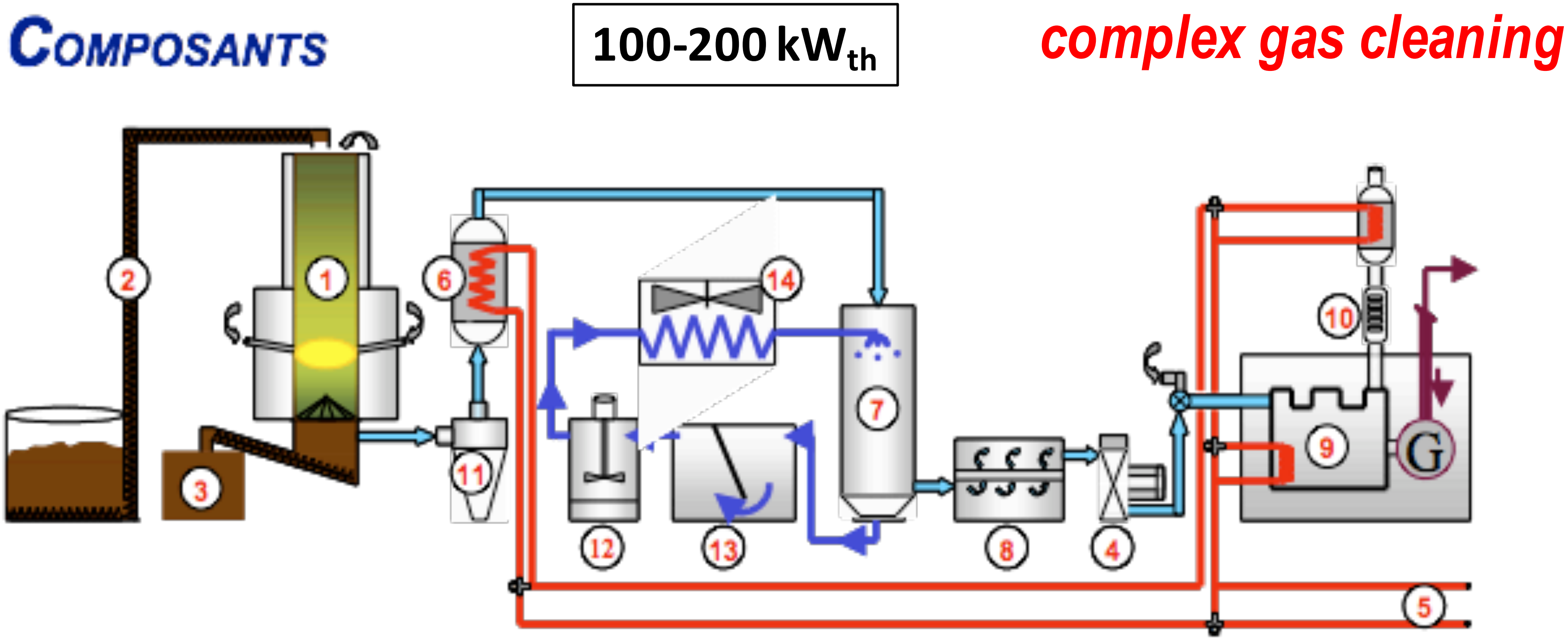
- What is the energy content per $m^3$ of producer gas? How does this compare to natural gas?
- What is the *'cold gas efficiency'* (=energy balance) of the process?

# Impurities from wood




- this is a complex issue for downstream *engines, turbines*,…
- tars = fuel (avoid condensation, but also fouling)
- cleaning needed (hot or cold)

# Wood gasification plant

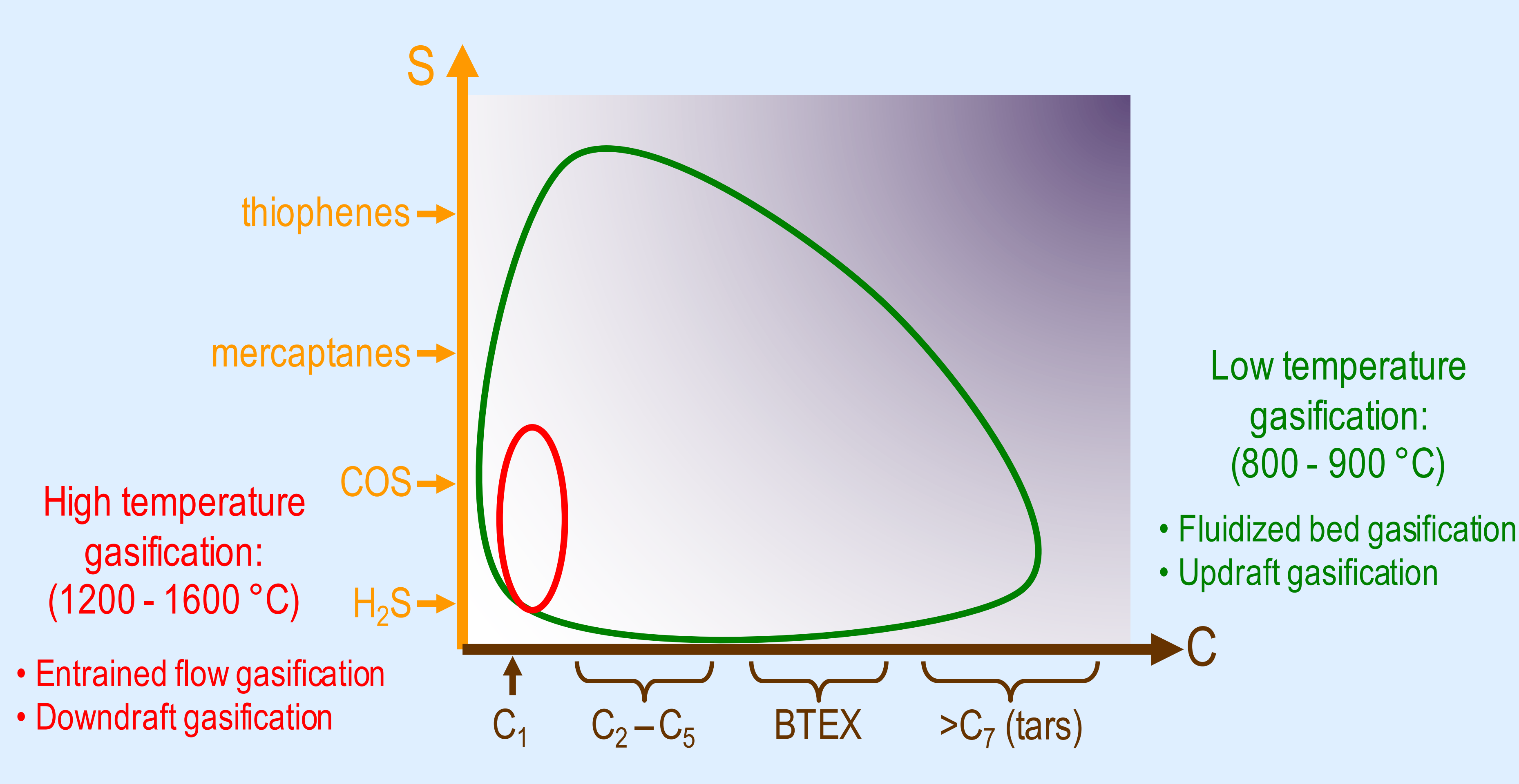



**Légende :**

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

# Impurities & potential contaminants

## Carbon- and sulphur-species in raw gas from gasifiers




*S. Biollaz, PSI*

# (Wood)Gas cleaning

- **Particulate matter (PM)**
  - scrubbing (<100°C, $H_2O$)
  - electrostatic precipitation (wet @65°C, dry @500°C)
  - cyclone (centrifugal)
  - (ceramic) filters

- **Alkali and halides**
  - they condense on PM

- **Tars** :
  - condense <100°C
  - they can be decomposed thermally (1000°C) or catalytically (800°C)

- **Sulphurs** :
  - thermally cracked to $H_2S$
  - absorb $H_2S$ on ZnO (400°C)

# Wood gasifier(15 $kW_{th}$) pilot lab

## Improved setup for long duration test

### Flexible setup for testing hot gas cleaning and high temperature fuel cells


Technical features

- ❑ Autonomous biomass-pellet operation with big bag (600 kg)
- ❑ Updraft gasifier (2 kg/h, 0.3 bar)
- ❑ Hot gas filter (400 – 550°C)
- ❑ SMR, ATR (700 - 900°C)
- ❑ Inertial filter at 650°C & 400°C
- ❑ Autonomous sampling system for gas analysis.
- ❑ Monitoring of gas composition with μGC (24/24 h)
- ❑ Automatic cell phone alarm in case setup is leaving prefixed operation window
- ❑ Remote control

# Hot gas cleaning (candle filter)

## Result of 400 h duration test of hot gas filter

### Successful removal of dust from raw gas, improvements required on ash handling


Clean gas chamber/safety elements without tar condensation at 450°C

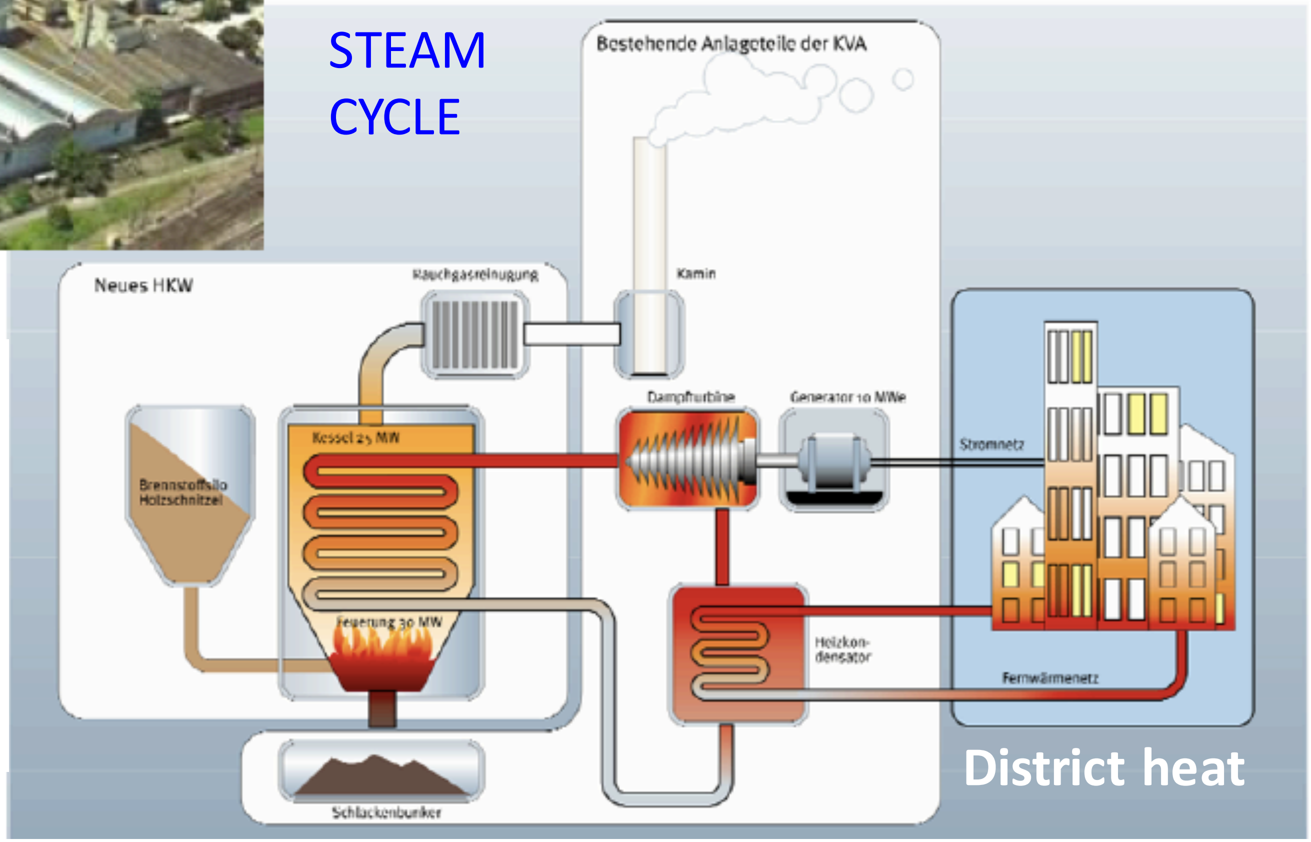
In total 480 kg wood pellets were gasified and 7.1 kg ash removed

Raw gas chamber completely filled with ash (2 kg)

# Waste incineration plant (incl. wood waste)


S. Biollaz, PSI-TPE

<u>Basel (CH)</u>
30 $MW_{th}$, **4 $MW_e$**, 21 $MW_{heat}$
since 2008
170'000 $m^3$/yr = 43'000 t/yr




<u>Zürich (CH)</u>
42 $MW_{th}$,
**11 $MW_e$**, 28 $MW_{heat}$
since 2010
265'000 $m^3$/yr=66'000 t/yr

# Co-combustion / Co-gasification wood+coal

S. Biollaz, PSI-TPE


http://www.bbc.com/news/science-environment-20269615

<u>Coal plant Drax (UK)</u>
6 * 660 MWe
with **10% biomass** = **400 MWe**
1.5 Mt/yr biomass

<u>Co-gasification IGCC (NL)</u>
580 $MW_{th}$, 250 $MW_e$
with **10%-15% biomass** **(30 MWe)**
started in 1998 (with biomass: 2006)
100’000 t/yr wood

# Cogeneration / IGCC

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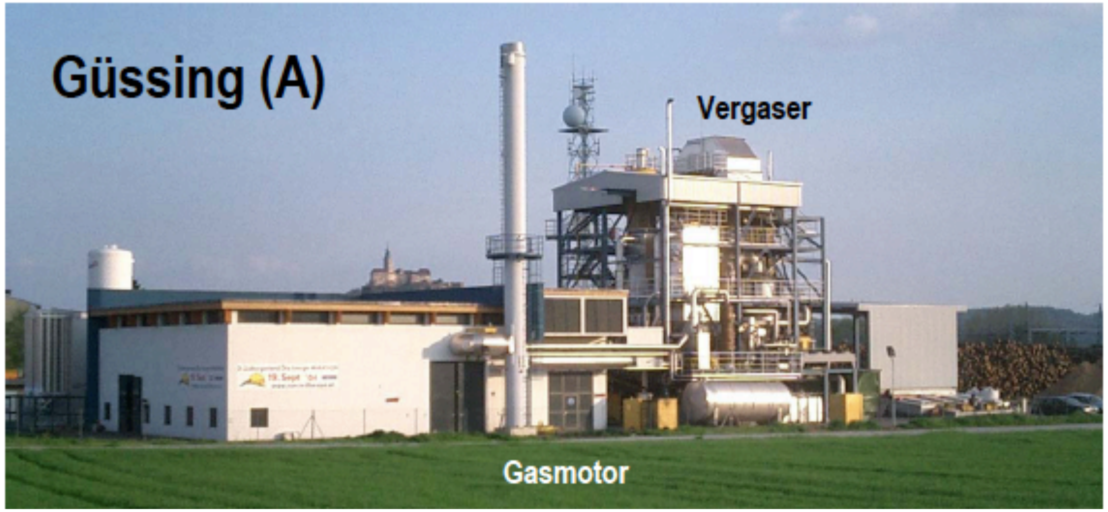




<u>Cogeneration, Güssing (AUT)</u>

8 $MW_{th}$, **2 MWe**, 4 $MW_{heat}$

Since 2002; 50'000 h operation

15'000 t/yr wood

<u>IGCC Värnamo demo (SWE)</u>

18 $MW_{th}$, **6 MWe**

1996-1999

7000 h operation

# Wood IGCC

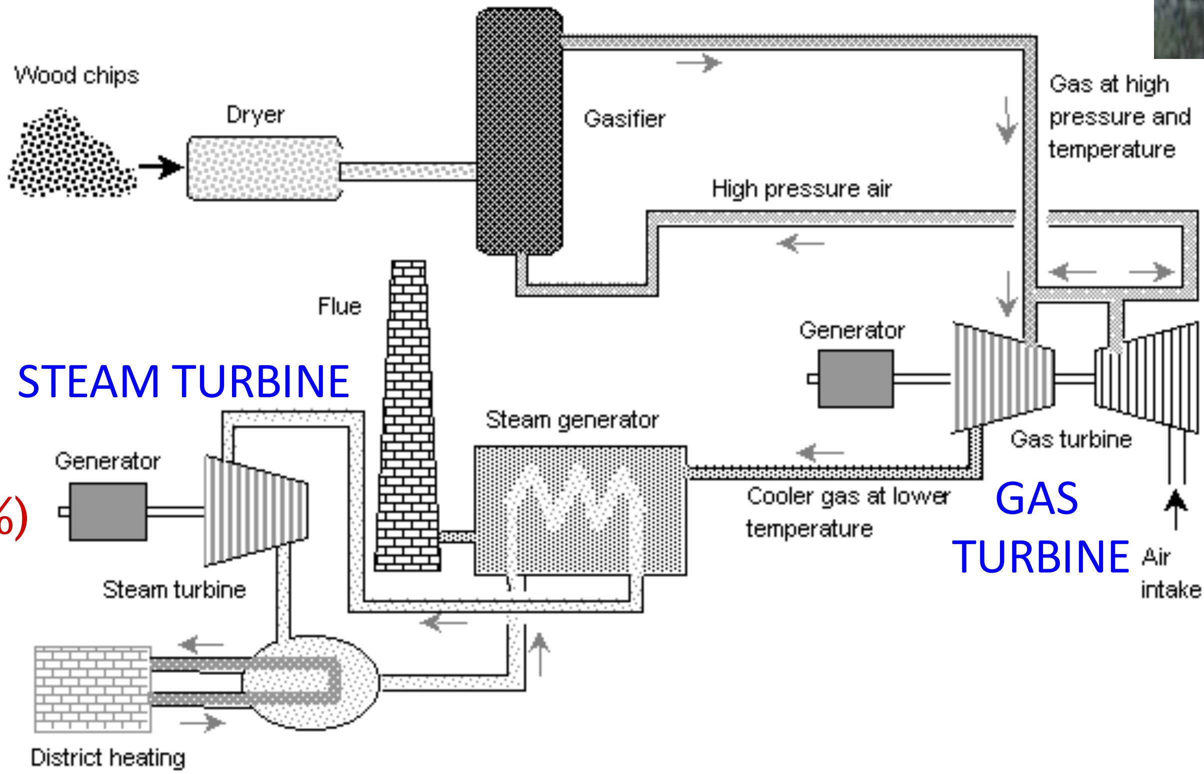
‘BIG-CC’ : Biomass Integrated Gasification combined cycle

Varnamo (SWE)

Fuel
18.3 MW

Electricity
6 MW (32%)

Heat
9 MW



# Electrical efficiencies from wood

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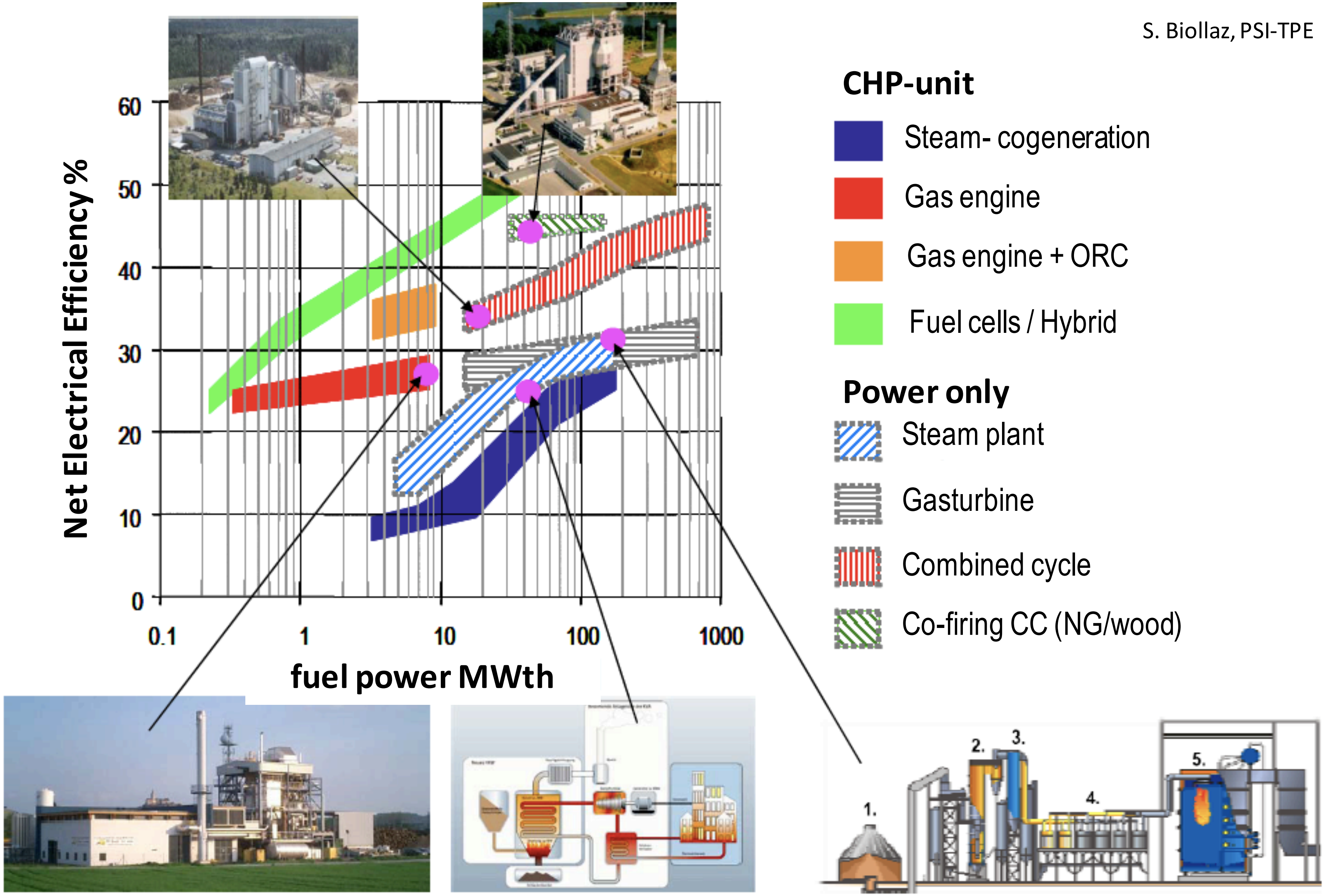
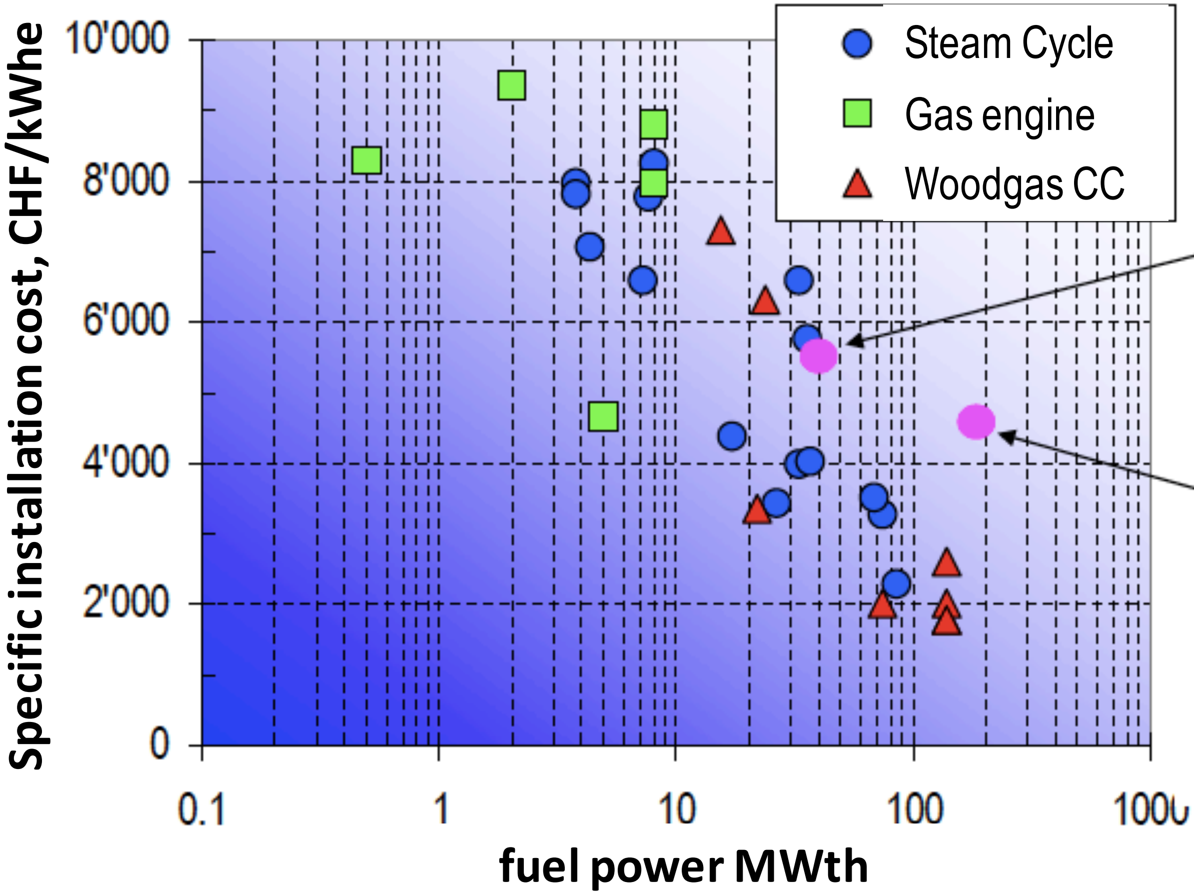
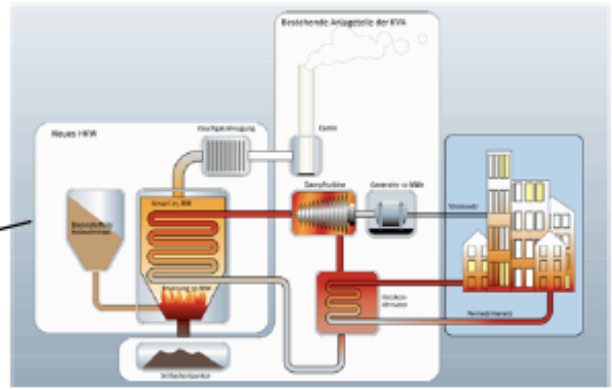
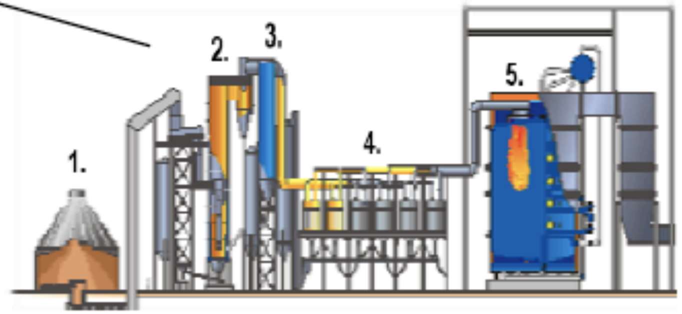


# Costs (wood → power)






http://www.youtube.com/watch?v=jbQ1hw7XQ0M

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# ‘Energy crops’ : characteristics
## (as opposed to food crops)

| Differentiation factors | Energy crops | Food crops |
| --- | --- | --- |
| energy balance (OUT:IN) | very positive | positive, but lower yield |
| plant utilisation | ≈ 100% | only a fraction is commercial |
| calorific value | as high as possible (incl. weeds, organotoxic plants) | human nutritive value is the only priority |
| local environmental production | possible for wild plants, extreme conditions, marginal lands | traditional agriculture |
| nutrient recycling (as fertilizers) | yes (local exploitation) | no (consumption away from production site) |

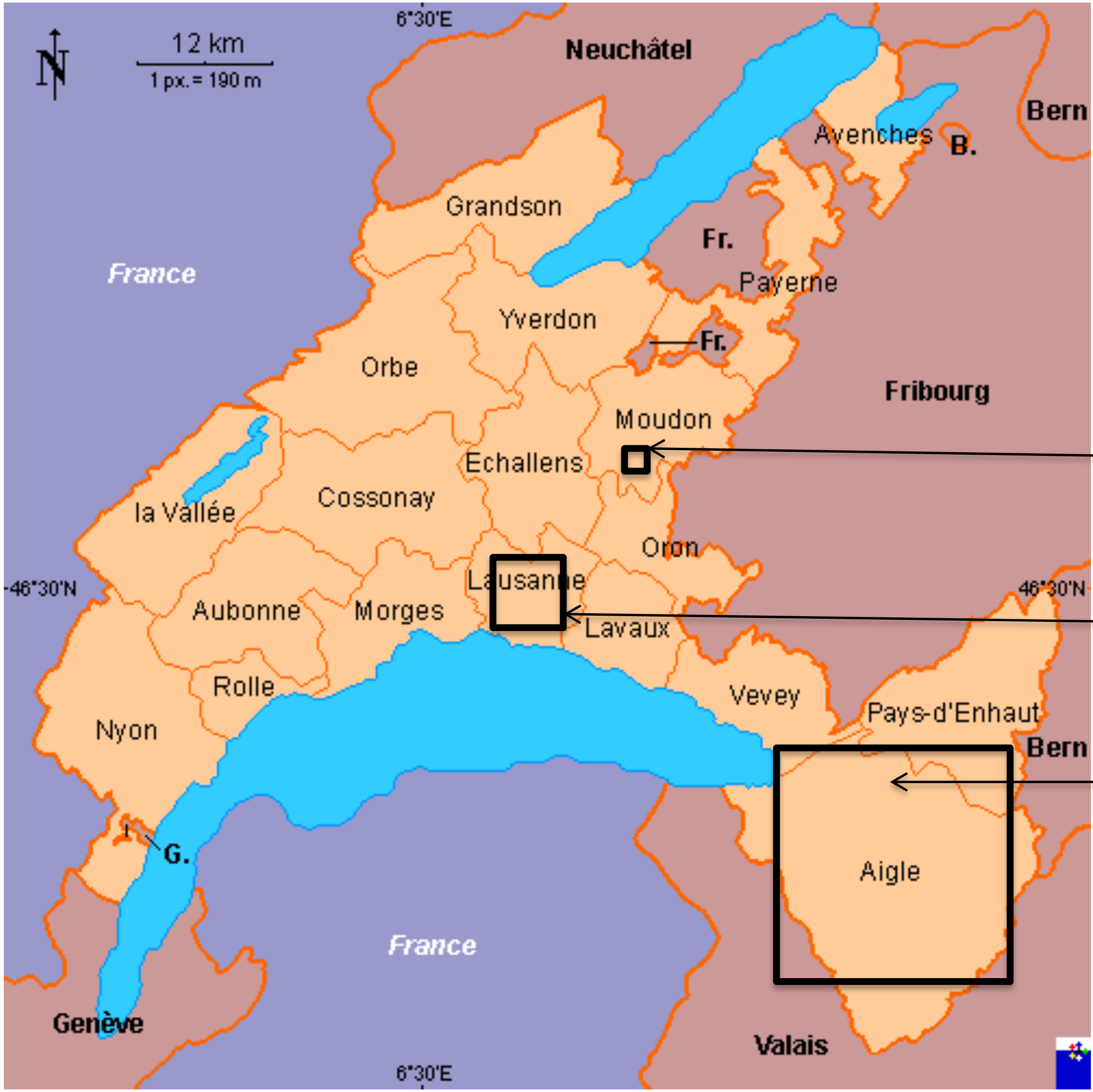
Possible energy crops : herbaceous, woody, aquatic

# Lignocellulosic energy crop plantations (woods, grasses)

- short rotation cycle (5 years, rapid growth)
- close spacing (< 1 m)
- species are available for *all climates*

| Climate | Examples |
|---|---|
| cold | bamboo, elephant grass |
| cold-temperate | willows, poplars |
| warm-temperate | eucaliptus, robinia/acacia, mimosa, **thistle** (**cynara** (*fr*.: *cardon*), of the artichoke family) |
| subtropical | pennisetum |
| wetlands | Provence cane, common cane |

# Plantation size needed




Assumptions:

1. 20 t dm/ha (340 GJ)
2. 8000 h/yr steam plant
3. 21 % efficiency:
   **1 kg biomass** (17 MJ)
   **= 1 $kWh_{el}$** (3.6 MJ)

1 $MW_{el}$ = 4 $km^2$ = 2 x 2 km

4000 $km^2$ would be required for a1 $GW_e$ plant. Biomass plant scale is therefore typically of 10 $MW_{el}$.

# Biomass = cheap fuel

- 300 € / ha with 20 tonnes dry matter (300 GJ)
  → **1 € / GJ** (thermal)
  → 2 ct € / $kWh_{el}$
- crude oil: 1 barrel = 159 L = ca. 6 GJ
  – at 65 $/barrel, oil cost is **11 $ /GJ**
- natural gas: **6.5 $ / GJ**
- coal price: 60 $ / tonne (=24 GJ) → **2.5 $ / GJ**