Biomass:
Wood conversion (and energy crops)

Learning objectives

- 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

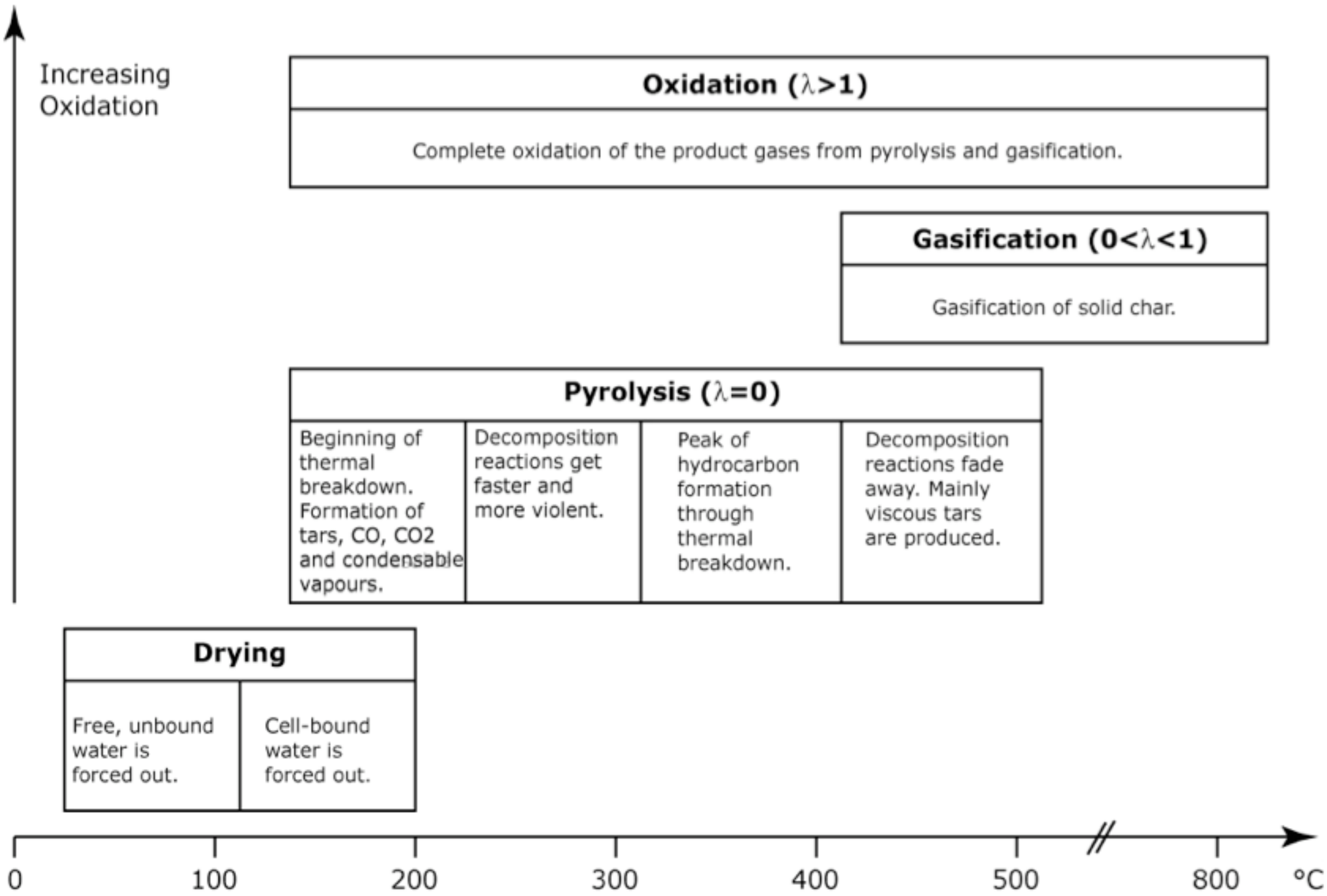
- Heat
- Woodgas
- Woodoil
- Biogas
- Bioethanol
- Biodiesel

Service

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

Combustion / Gasification / Pyrolysis

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



Thermochemical conversion :

Process	T(°C)	λ	Product
Pyrolysis	400-700	0	combustible gas + liquid + solid
Gasification	700-900	Air: 0.2 to 0.5 Steam: 0.4 to 3	Low LHV gas High LHV gas Incombustible solid
Combustion	800-1300	≥ 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 instead
- 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

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

  '*<u>green</u>*' wood: 25-65% humidity
- *<u>'captive'</u>* humidity: H_2O retained *within* the fibres; this water is removed **irreversibly** when dried (and the fibres then contract)

  '*<u>free</u>*' 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

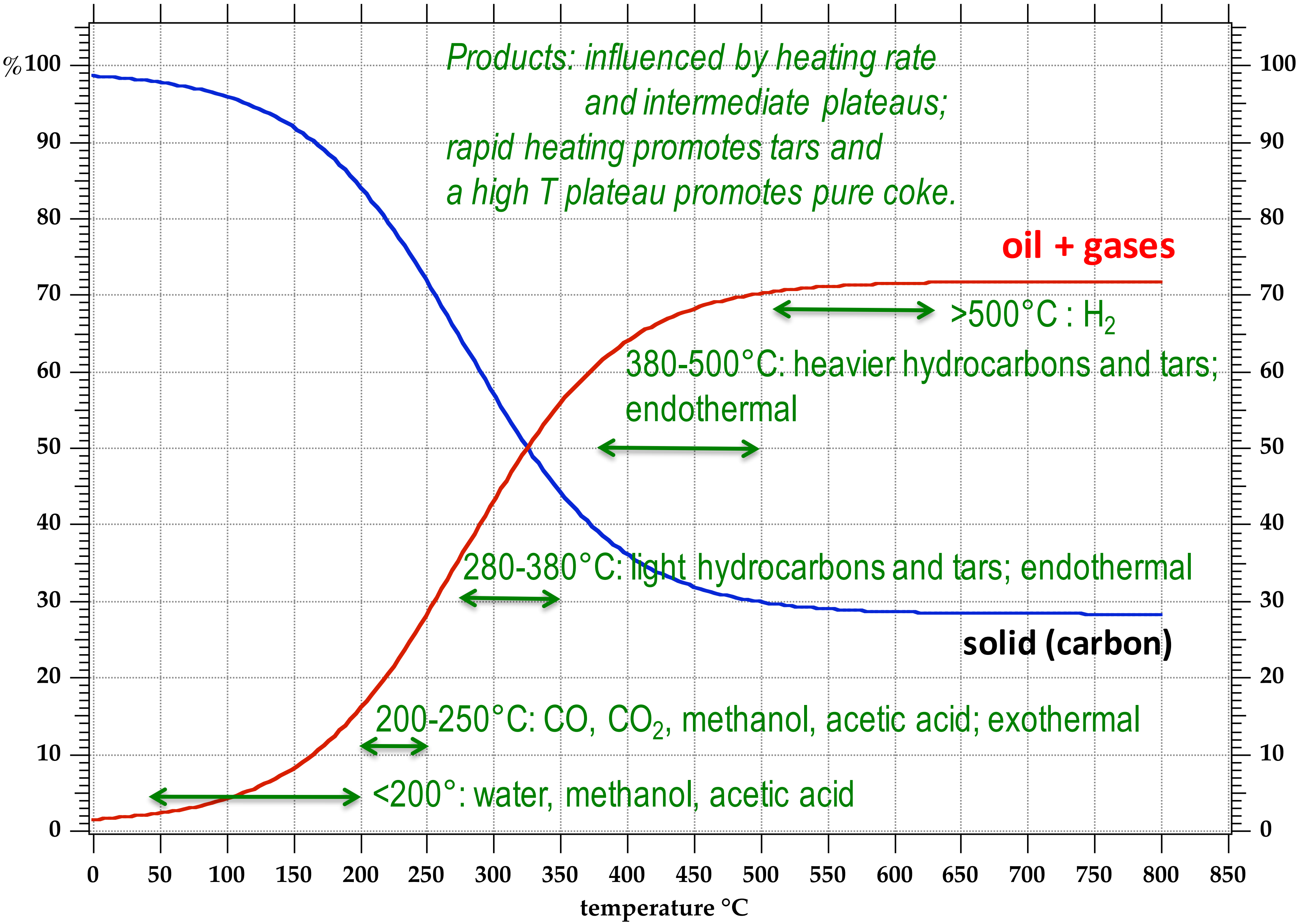
$$LHV_{humid} = LHV_{dry} * (1 - 1.14 * W)$$

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)



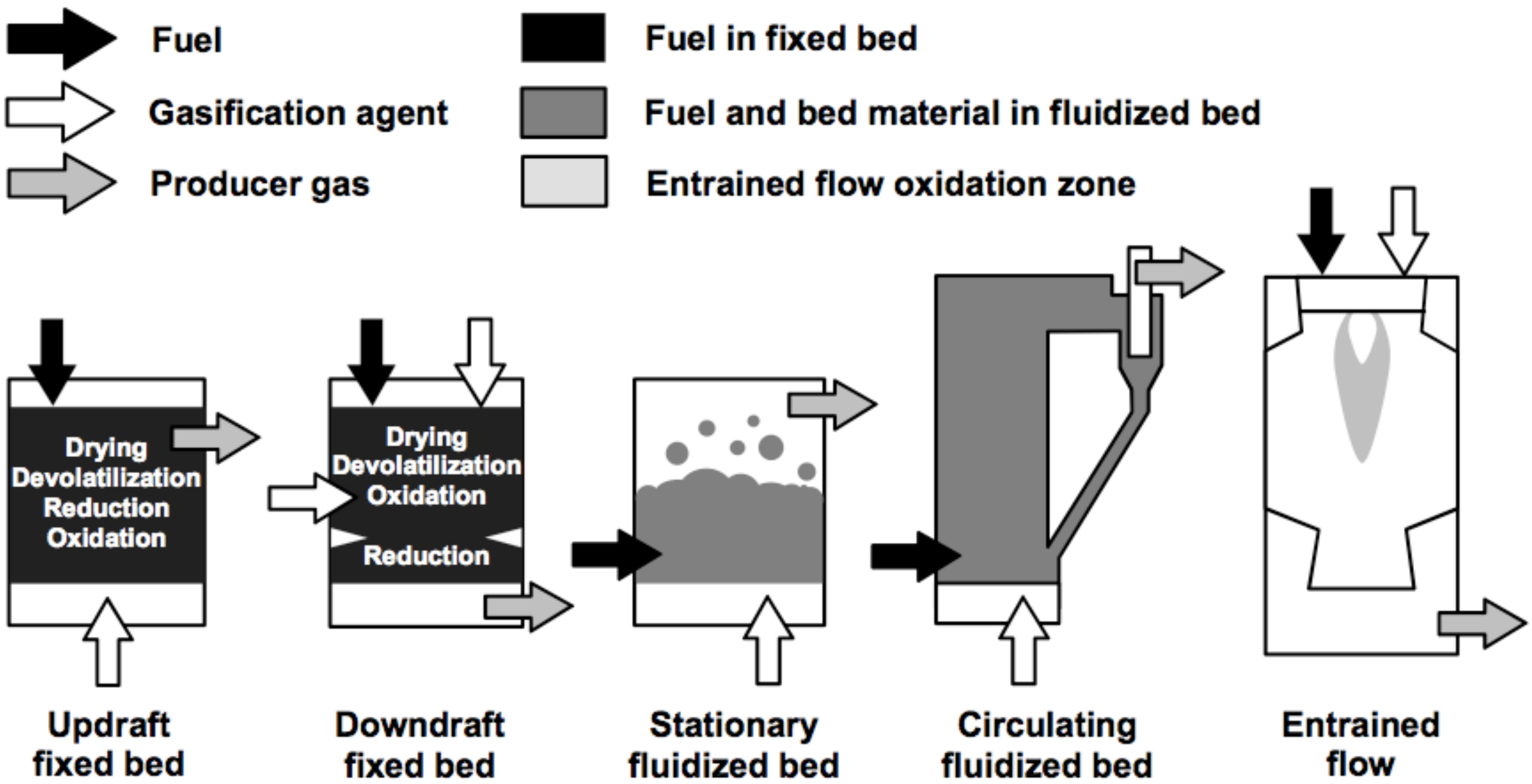
Pyrolysis energy balance *(cf. exercise)*

- Input:
  - 17 MJ/kg dry wood
  - heat supply (endothermal) : 2.4 MJ
    (=delivered from burning the liberated gases)
- 1 kg dry wood delivers:
  - 200 L of gas with a LHV equal to 1/3 that of natural gas (per m^3)
  - 0.45 kg of liquids with a LHV equal to 1/3 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

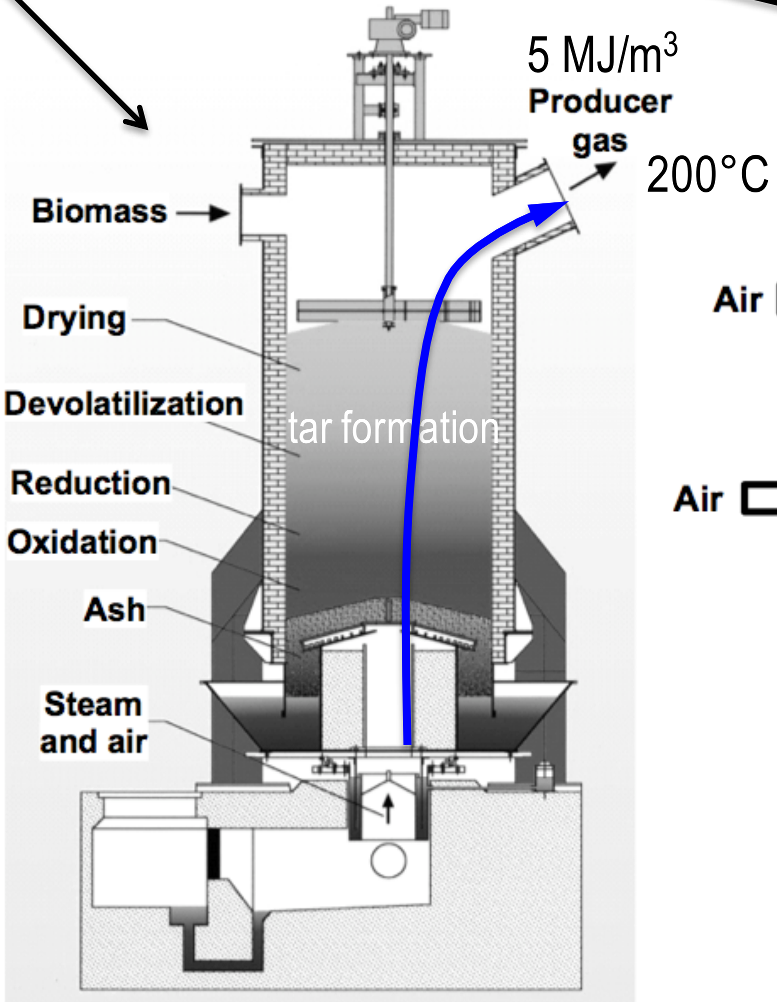
3. Gasification agent
   - air (exo)
   - O_2 (exo)
   - steam (endo)

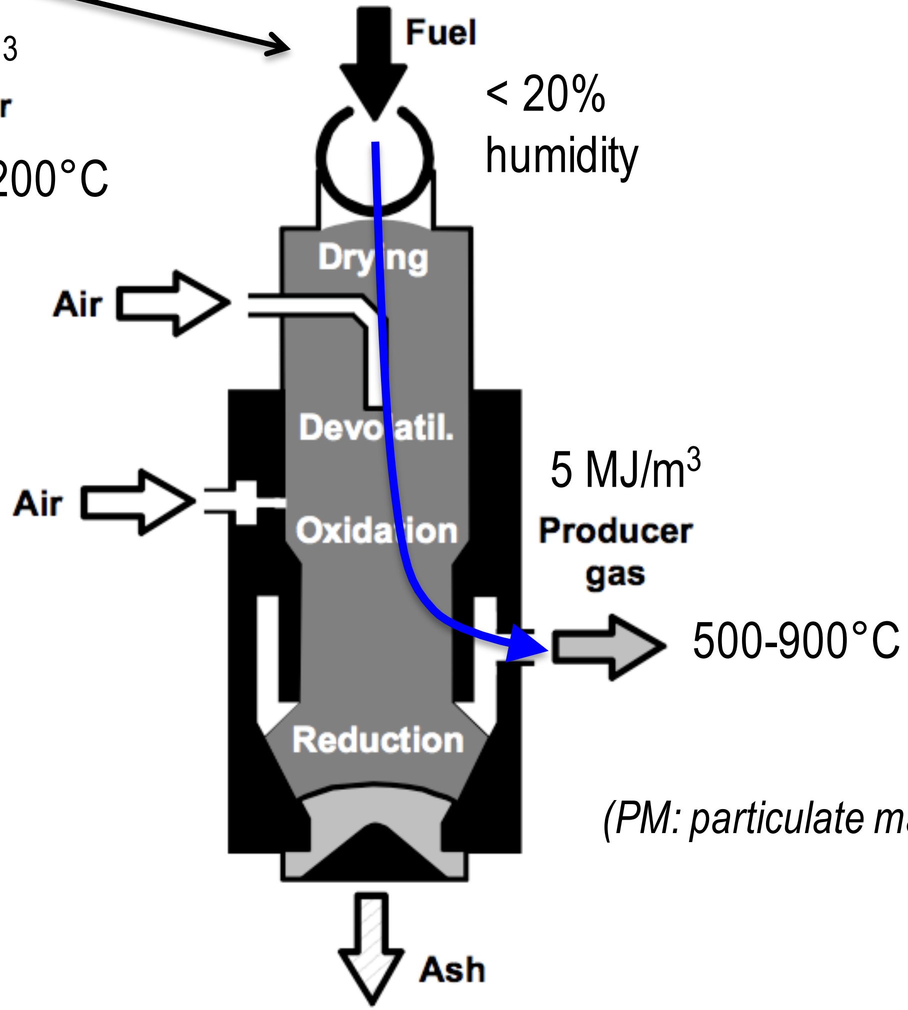
4. Stages
   - single
   - two

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

Updraft / Downdraft (fixed beds)

F. Nagel, PhD thesis, PSI (2010)





(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)

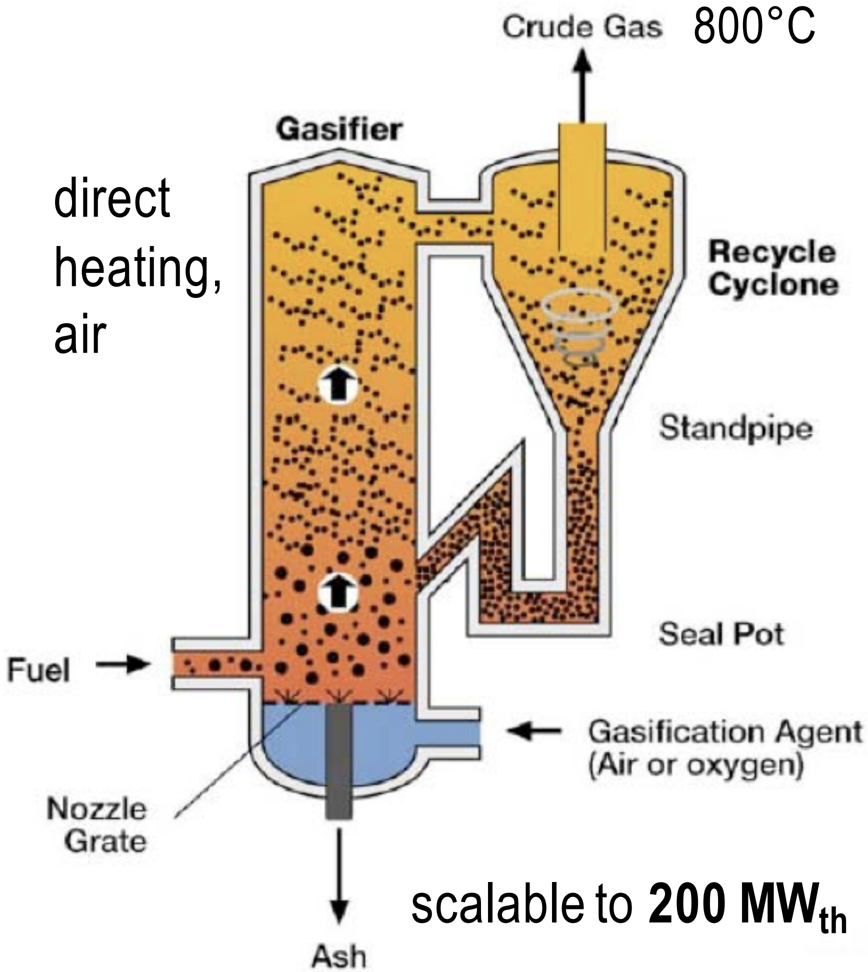
no distinct temperature zones like for up/down-draft; isothermal due to the circulation

CFB

5 MJ/m³

800°C

direct heating, air

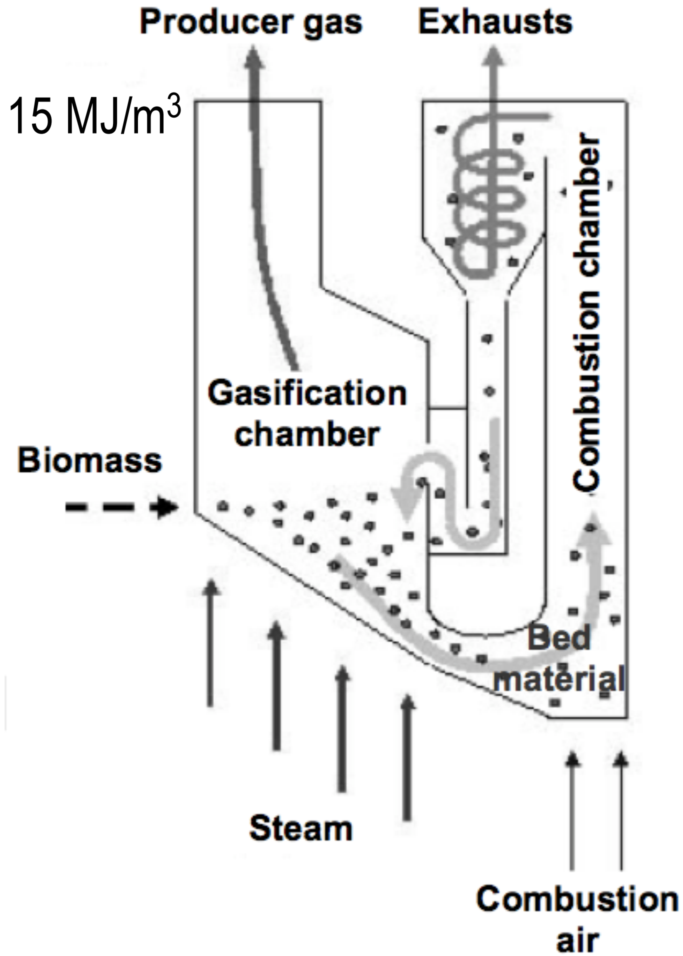


scalable to **200 MW$_{th}$**

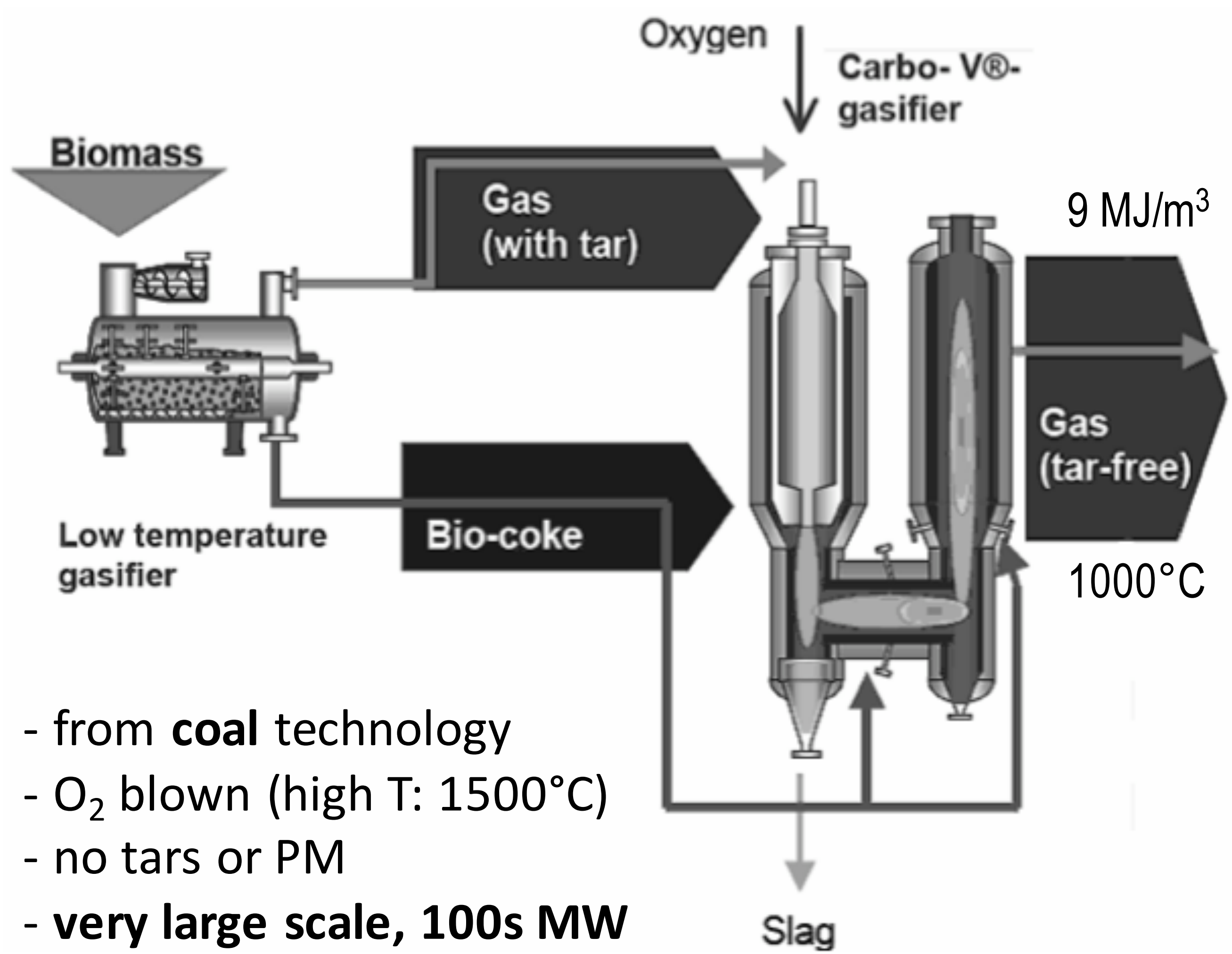
FICFB (Fast Internally CFB)

15 MJ/m³

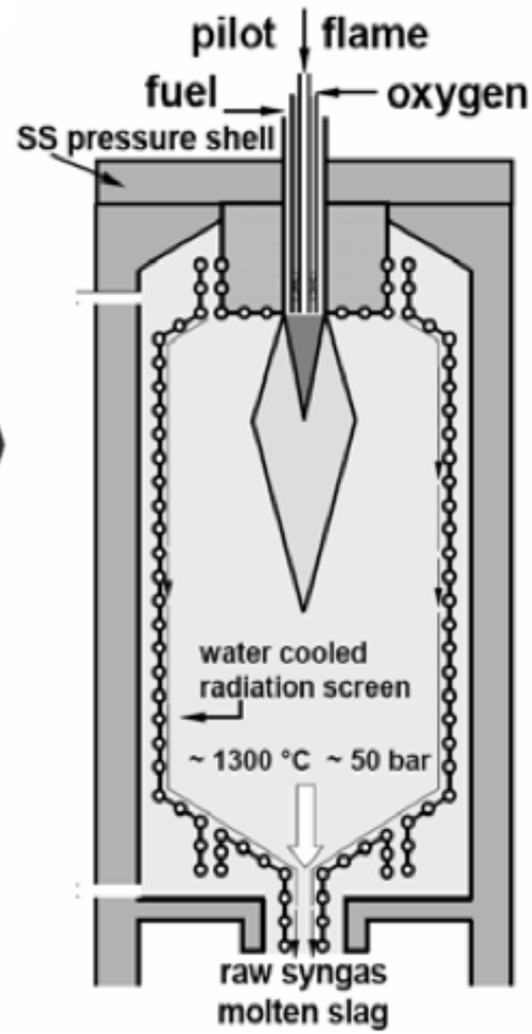
indirect heating, steam



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) *(exercise)*

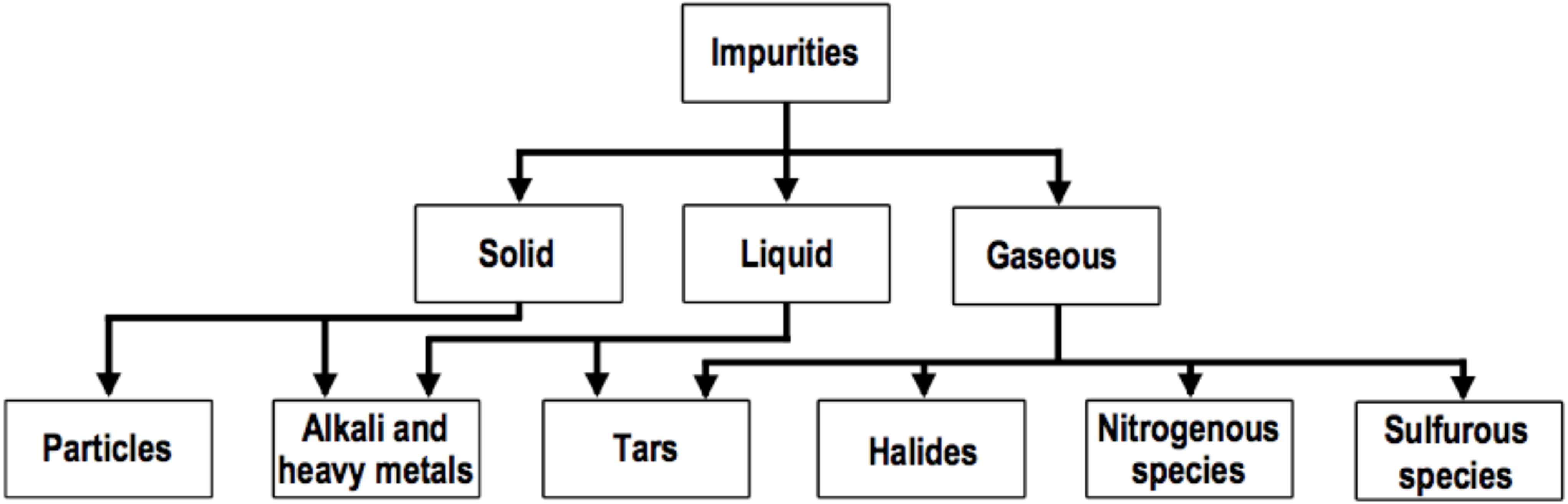
- Input 1 kg dried wood (15wt% residual humidity)
- delivers 2 m^3 producer gas of :

  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



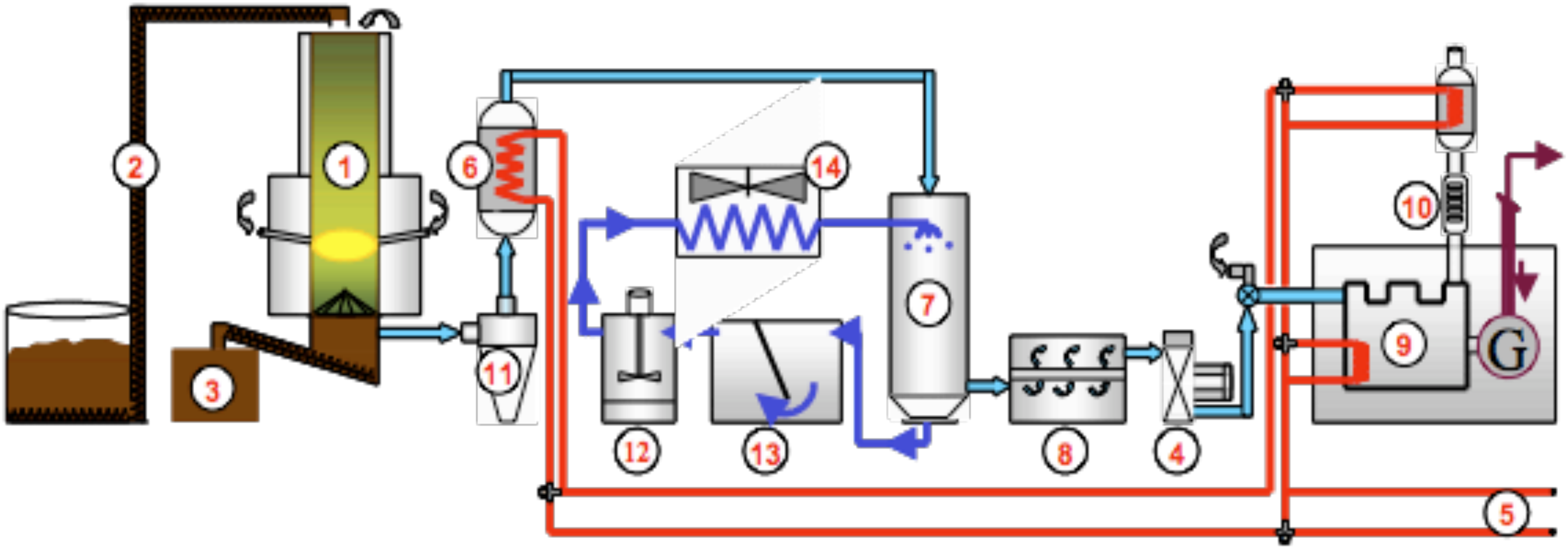
- this is a complex issue for downstream *engines, turbines*,…
- tars = fuel (avoid condensation, but also fouling)
- cleaning needed (hot or cold)

Wood gasification plant

COMPOSANTS

100-200 kW_{th}

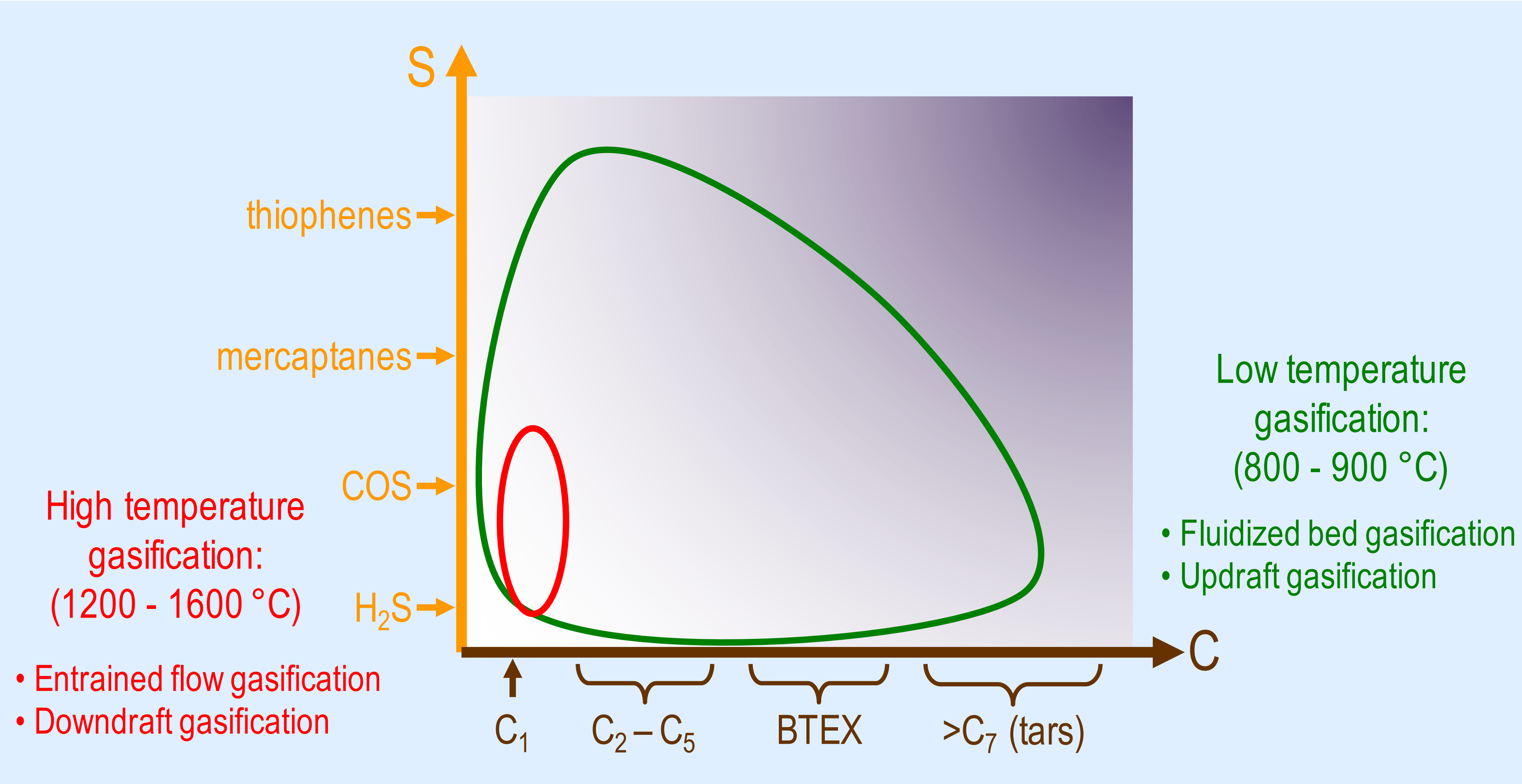
complex gas cleaning



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	

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

PAUL SCHERRER INSTITUT PSI

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 with tar condensation at 350°C

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)

Cleaned raw gas chamber

Screw for ash removal

Waste incineration plant (incl. wood waste)

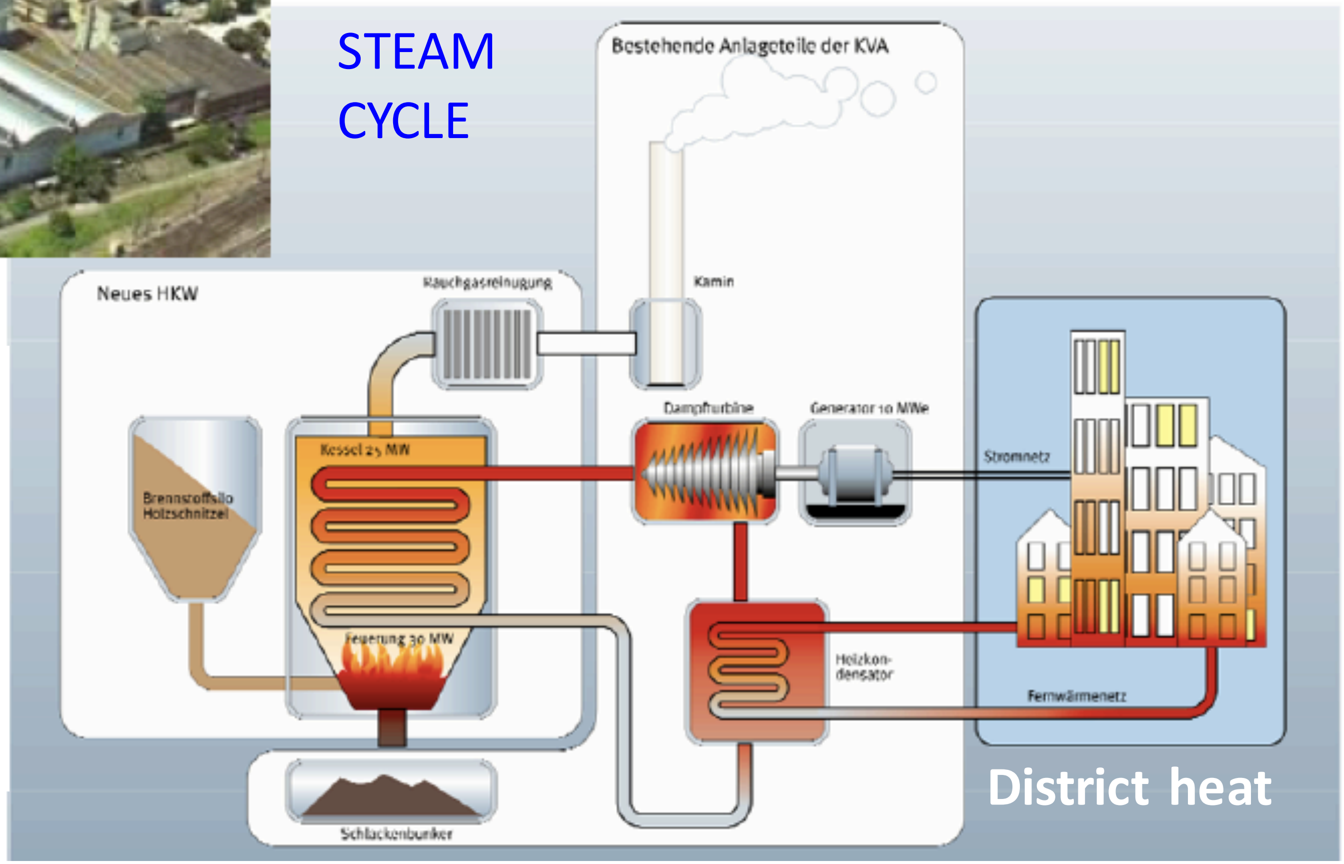
S. Biollaz, PSI-TPE

<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

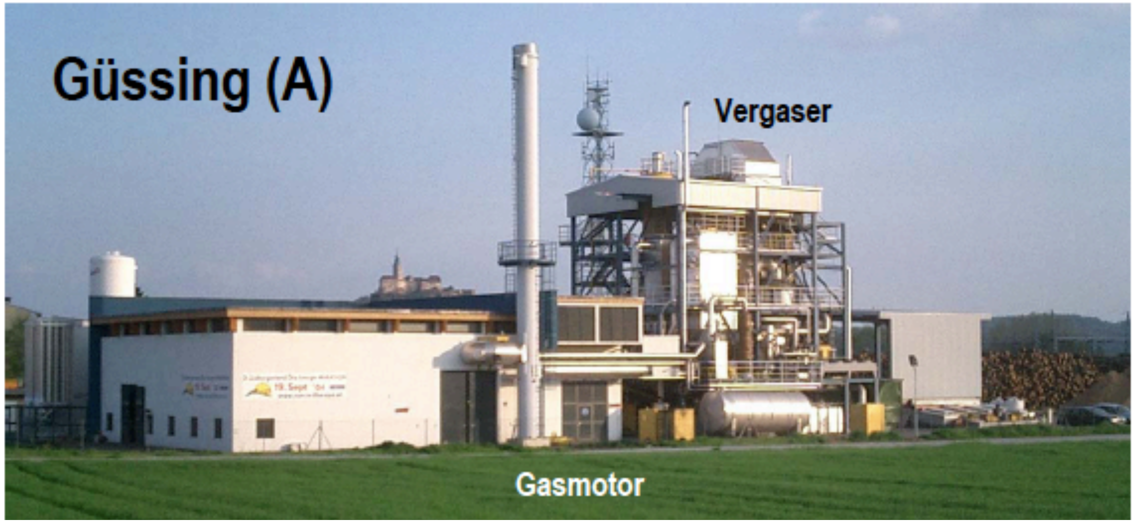
http://www.bbc.com/news/science-environment-20269615

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

Co-gasification IGCC (NL)
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

S. Biollaz, PSI-TPE



<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

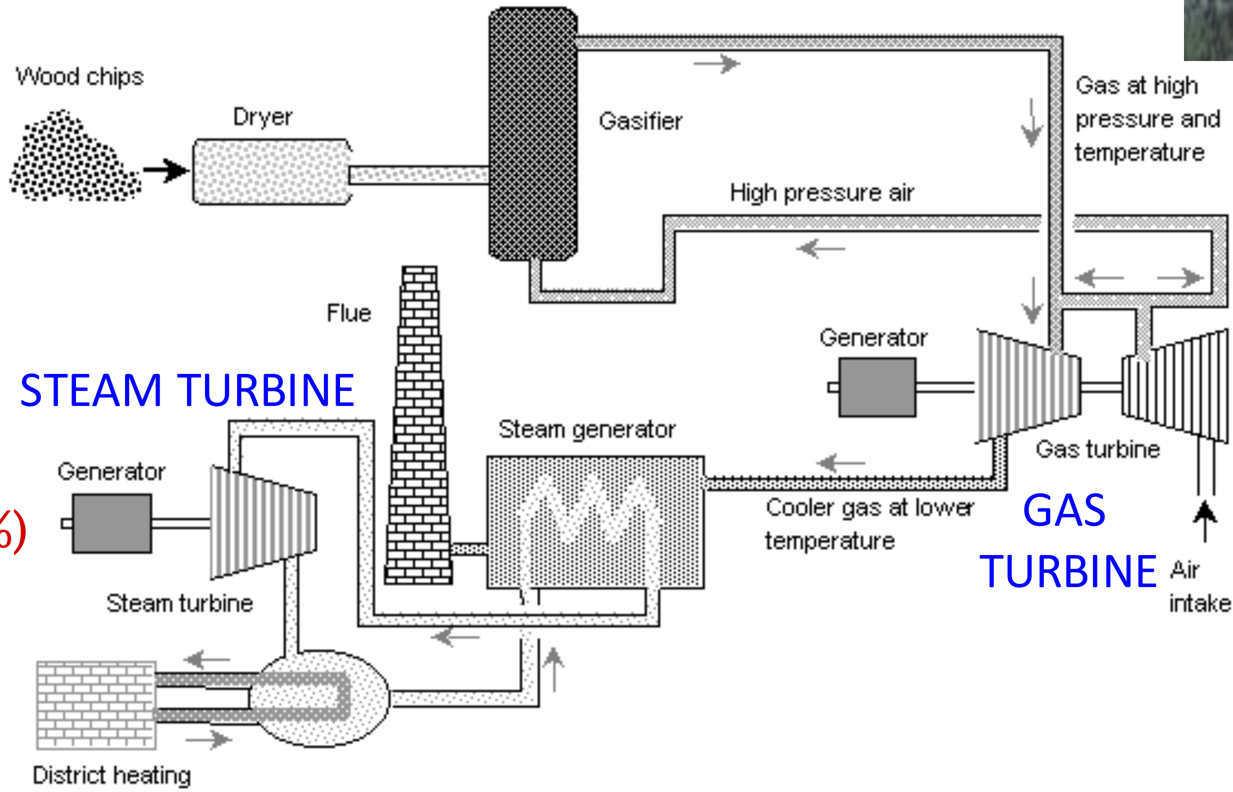
'BIG-CC' : Biomass Integrated Gasification
combined cycle

Varnamo (SWE)

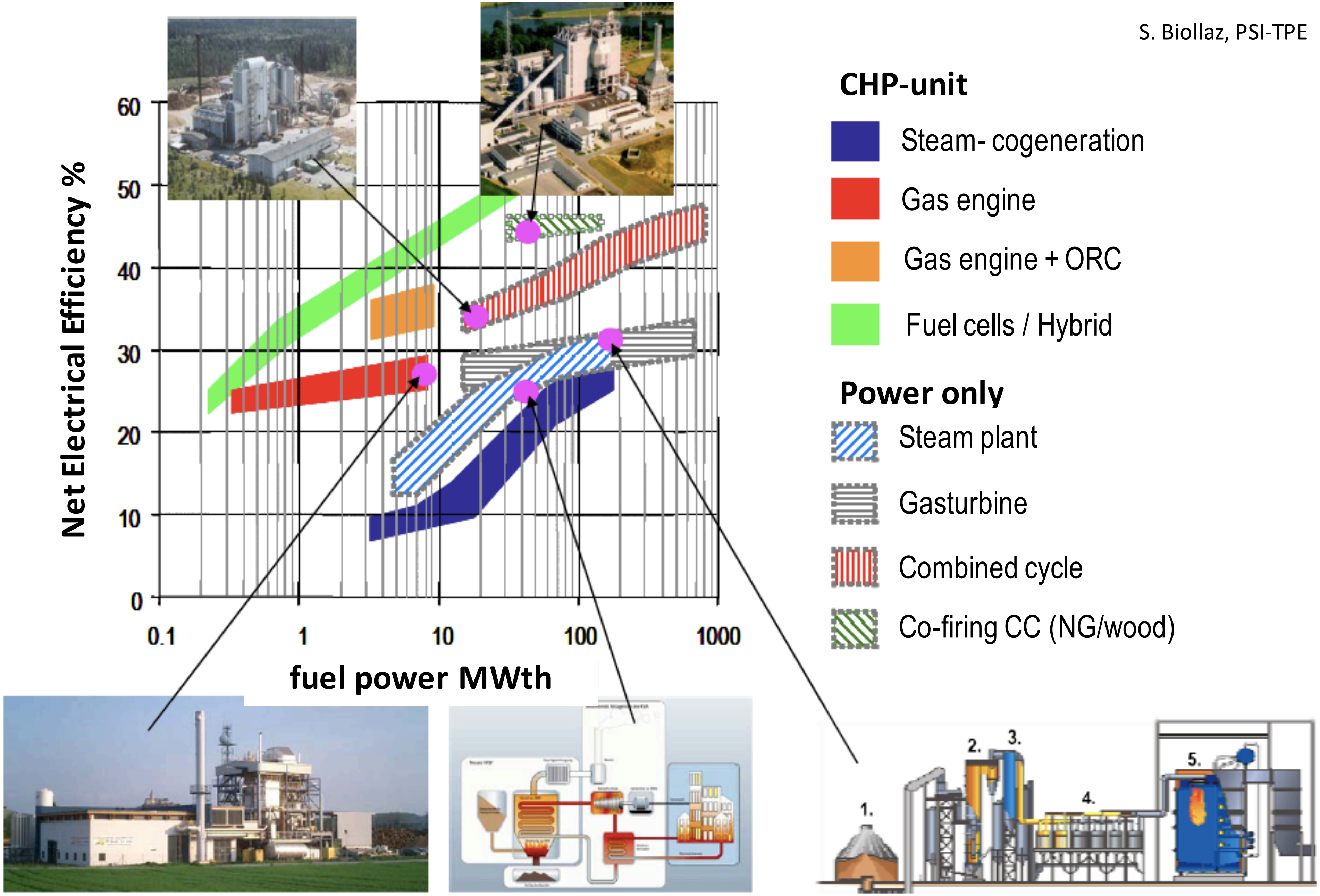
Fuel
18.3 MW

Electricity
6 MW (32%)

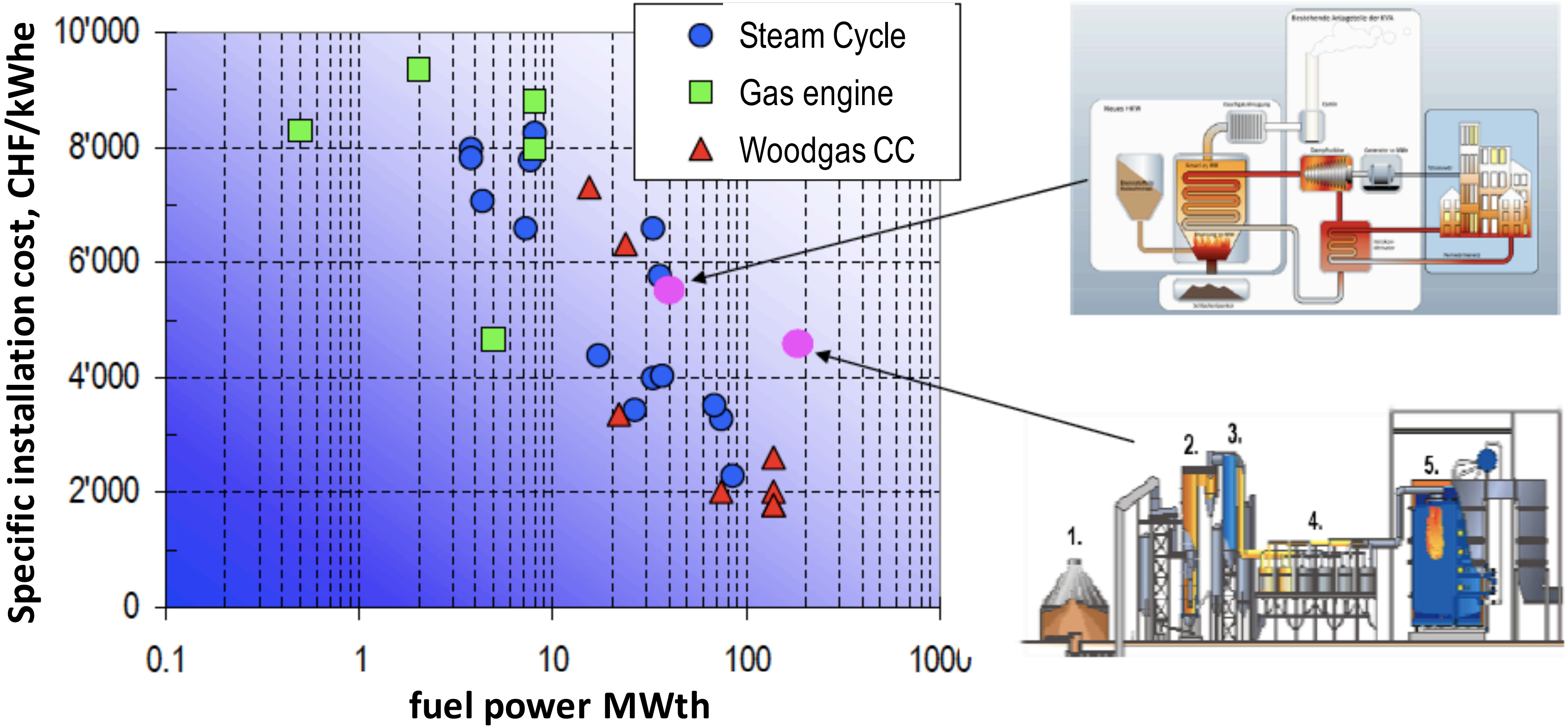
Heat
9 MW



Electrical efficiencies from wood



Costs (wood → power)



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

S. Biollaz, PSI-TPE

‘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)

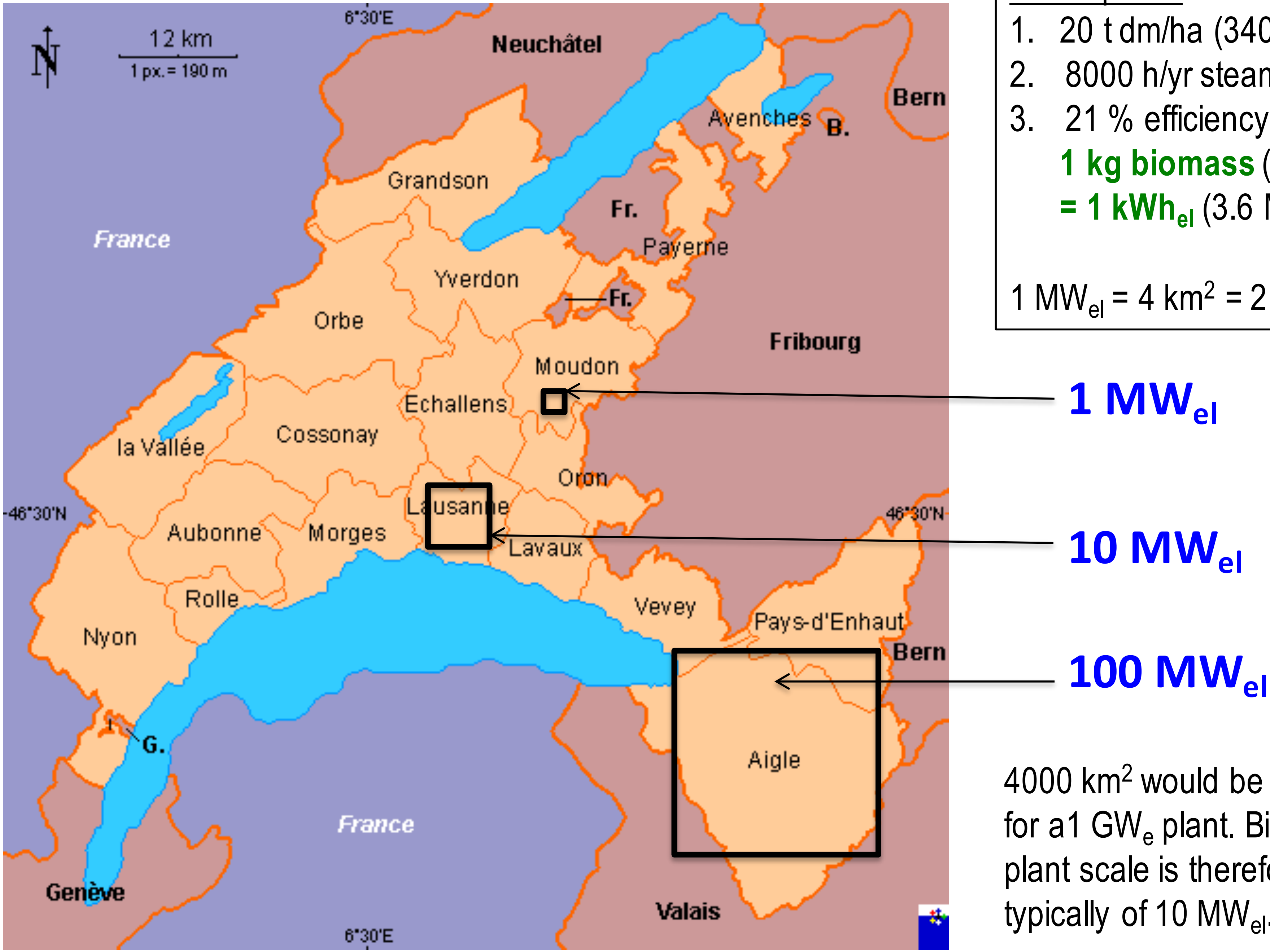
Possible energy crops : herbaceous, woody, aquatic

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 50 $/barrel, oil cost is **9 $ /GJ**
- natural gas now: **2 $ / GJ** (but as household = 17$/GJ)
- coal price: 45 $ / tonne (=24 GJ) → **2 $ / GJ**