

Biomass: solids

Wood conversion (& energy crops)

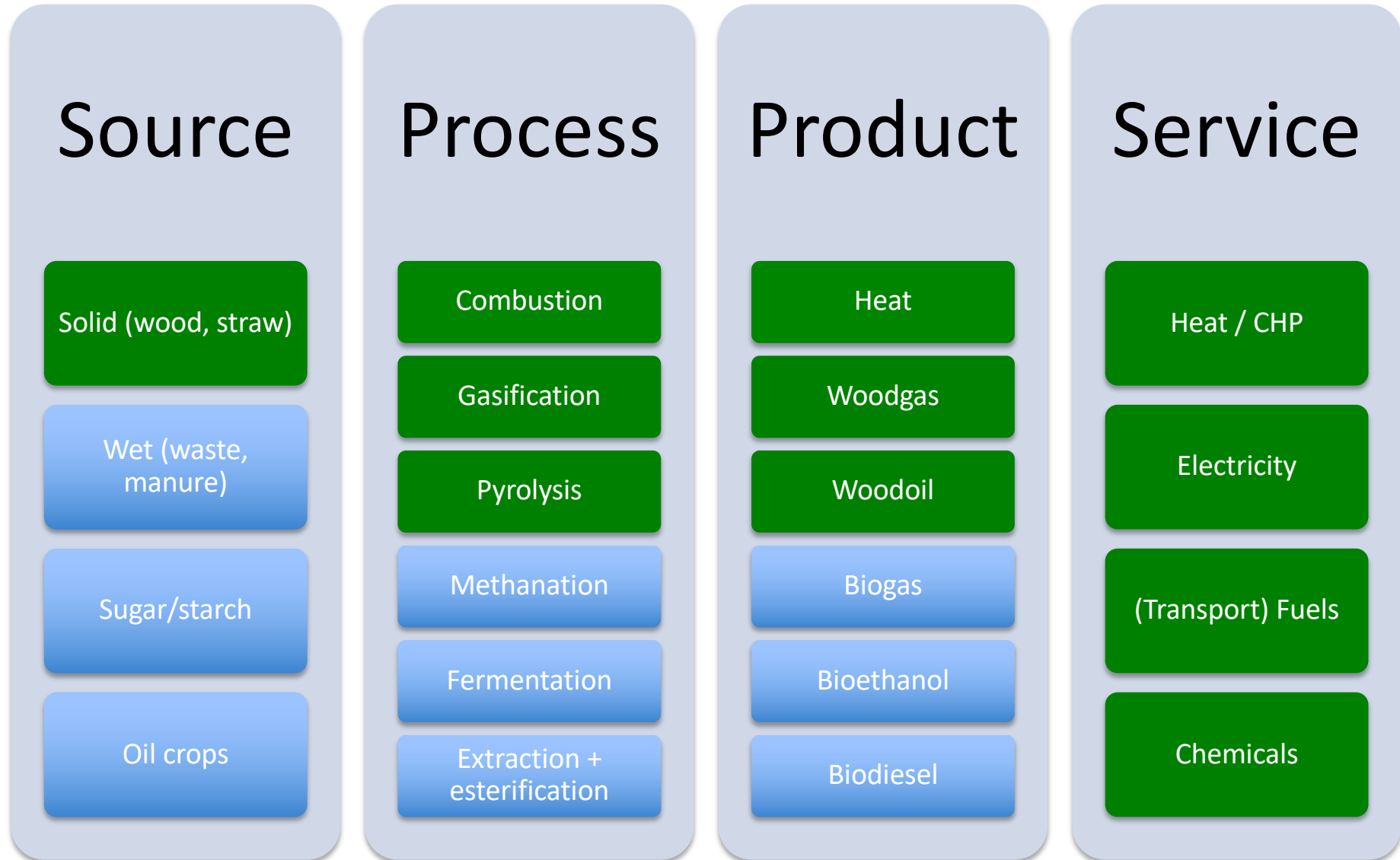
Learning objectives

- Distinguish **pyrolysis** / **gasification** / **combustion** of wood
- Different (wood) **gasification concepts** and their basic characteristics
- Wood **impurities**, and cleaning processes
- Uses of wood (/solid wastes) in **power plants**, their power **sizes** and electrical **efficiencies**

Uses of wood - general

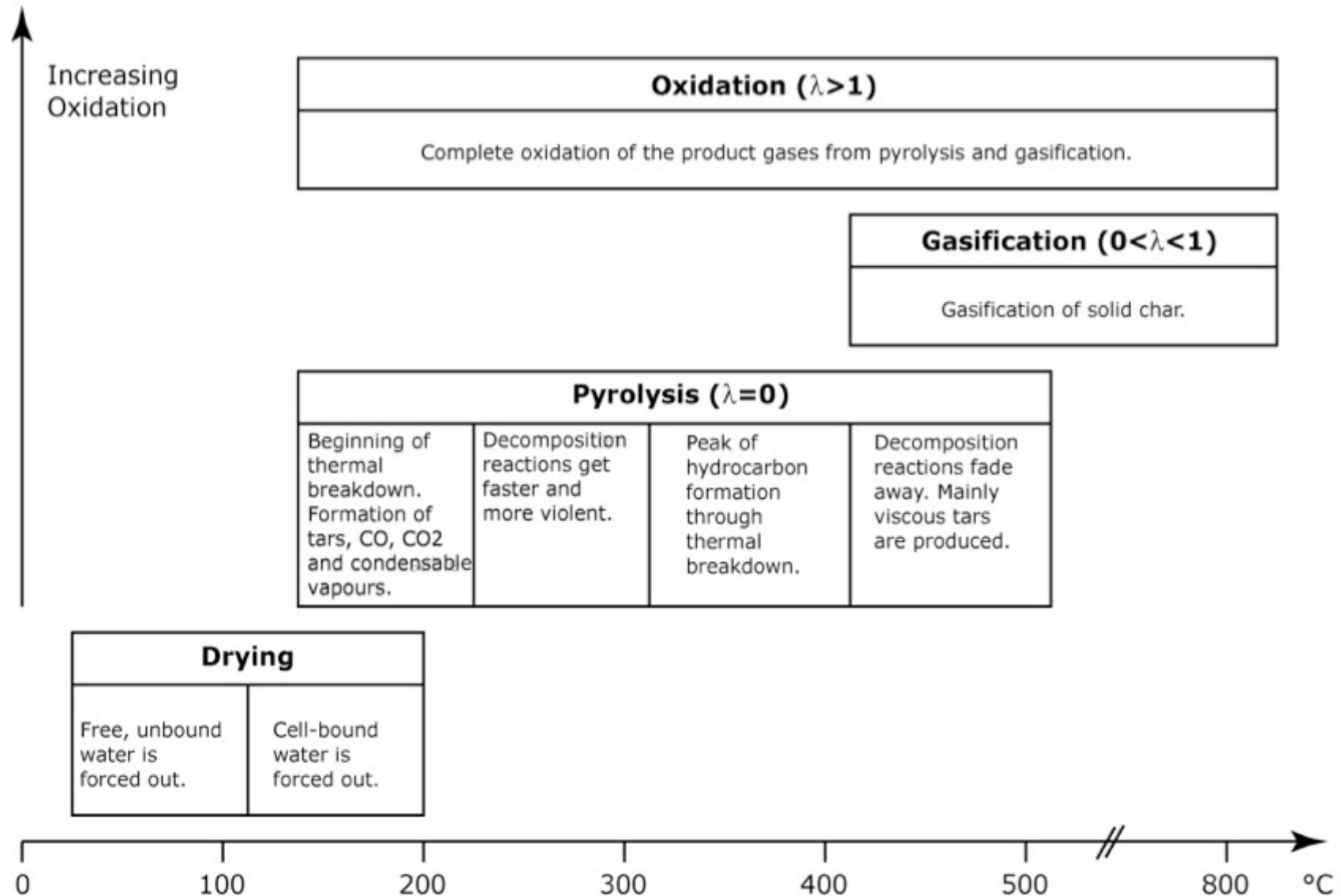
- **energy** use:
 - ~50% of forest 'waste'
 - mostly in direct combustion for heat
- **other** uses:
 - construction, furniture, packaging
 - paper production
 - wood chemistry (*xylochemistry*): CH_4 , alcohols, pharmaceuticals
 - annex products: cork, resin, rubber, tannins,...

Biomass roadmap: energy uses of wood



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)

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

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

- hardwood (oak, beech, maple, teak, walnut, poplar, birch):
22% lignine, 500 kg/m³, 19.5 MJ/kg, slow growth, dark color, loose leaves
- softwood (all pinewoods and resinous trees, cedar, larch):
29% lignine, 300 kg/m³, 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: H₂O retained *within* the fibres; this water is removed **irreversibly** when dried (and the fibres then contract)

'free' humidity: H₂O 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 H₂O replaces wood
 2. due to the evaporation heat required (2.44 MJ/kg H₂O)

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

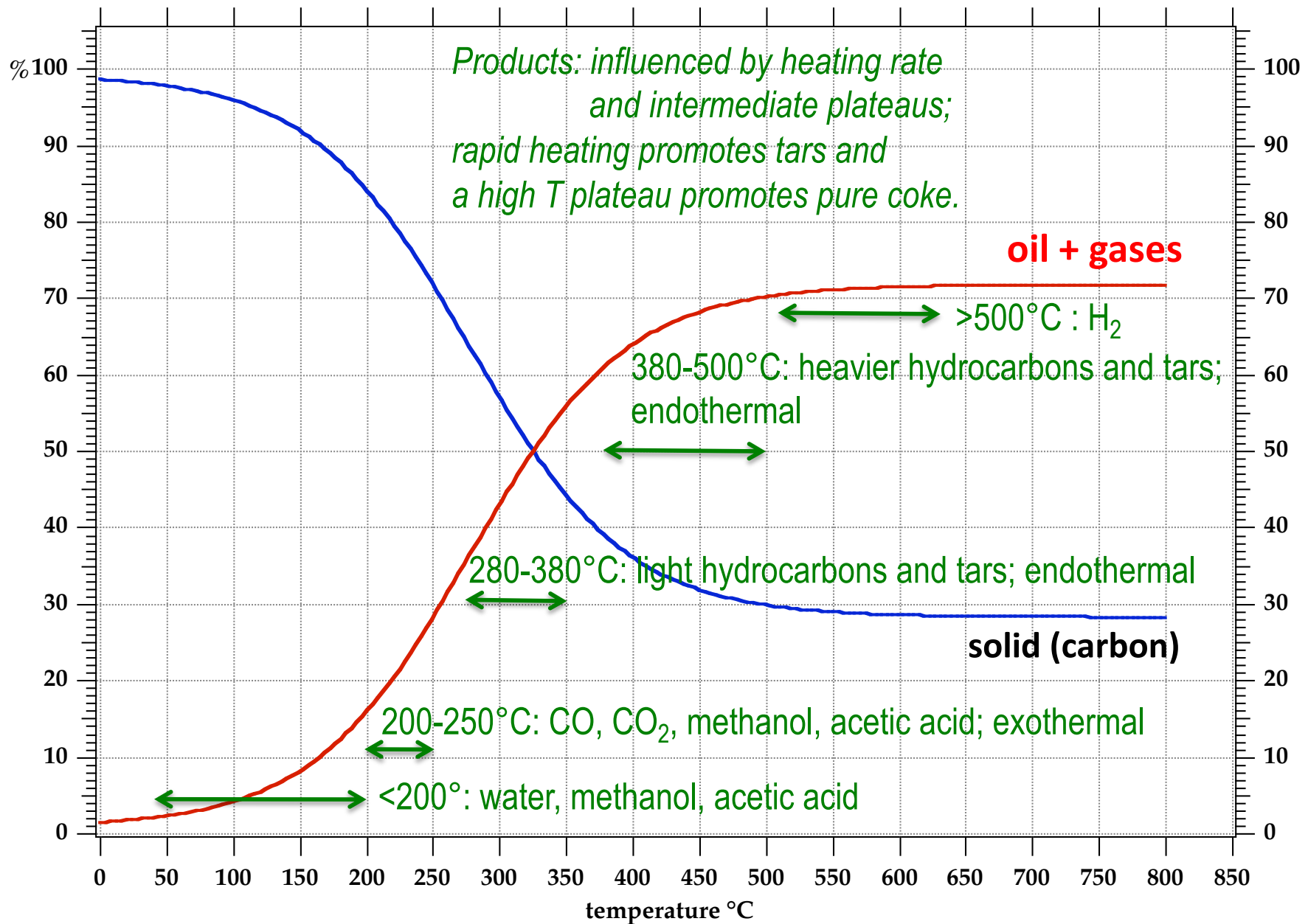
$$LHV_{humid} = LHV_{dry} * (1 - 1.14 * W)$$

W = water content in weight fraction

Pyrolysis (= “wood distillation”)

- 1000 kg dry wood generates:
 - 200 kg gas CO, H₂, CO₂, CH₄
 - 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)

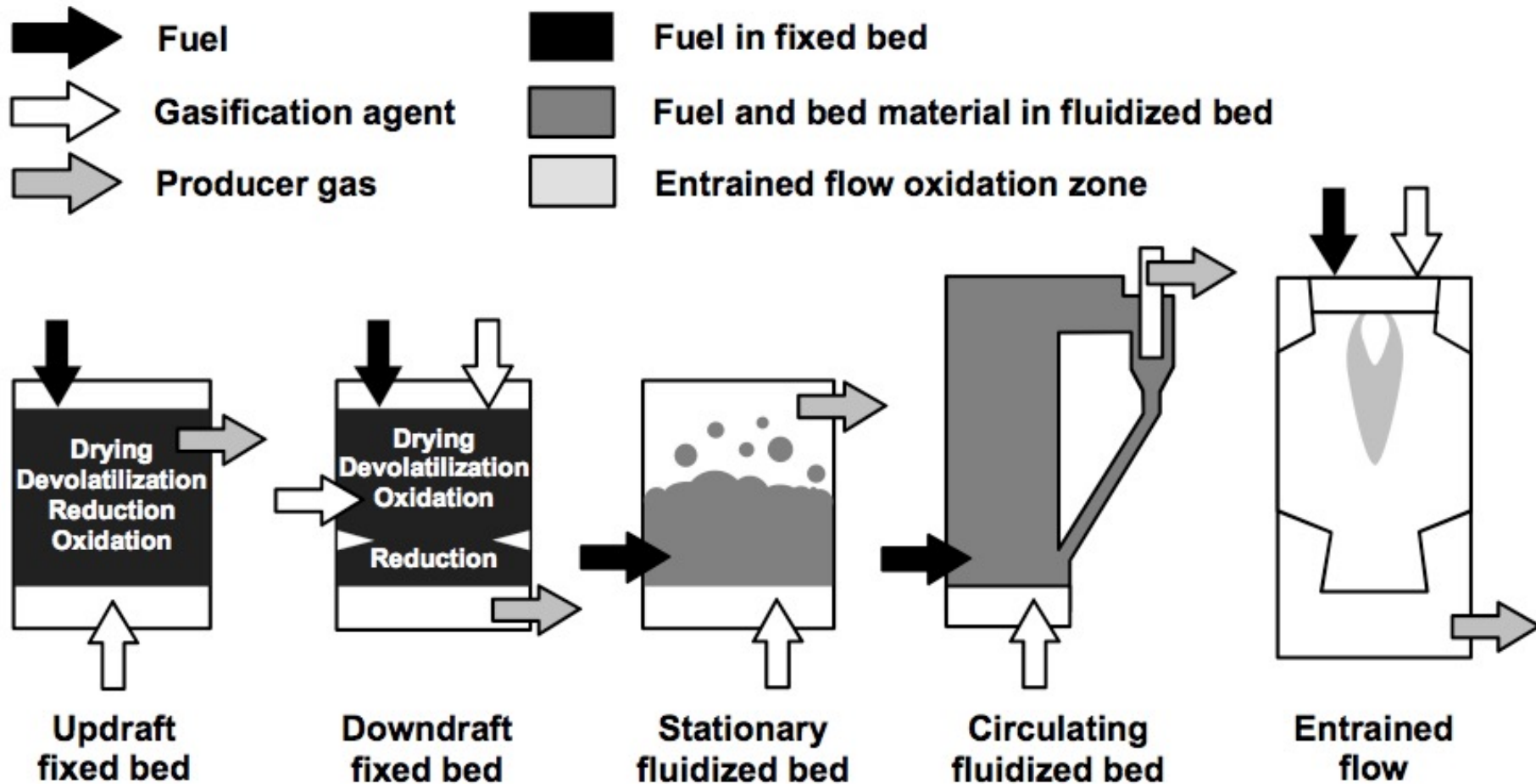


Pyrolysis energy balance *(cf. exercise)*

- 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 m³)
 - 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

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 _x H _y , tars, charcoal
Reducing	Endothermal	600-1000°C	reforming, shift, methanation reactions
Oxidising	Exothermal	1000-1600°C	CO ₂ , H ₂ O

Classification of gasifier concepts:

1. Reactor type

- *fixed* bed
- *fluidised* bed
- *entrained* flow

2. Heat supply

- direct
- indirect

3. Gasification agent

- air (exo)
- O₂ (exo)
- steam (endo)

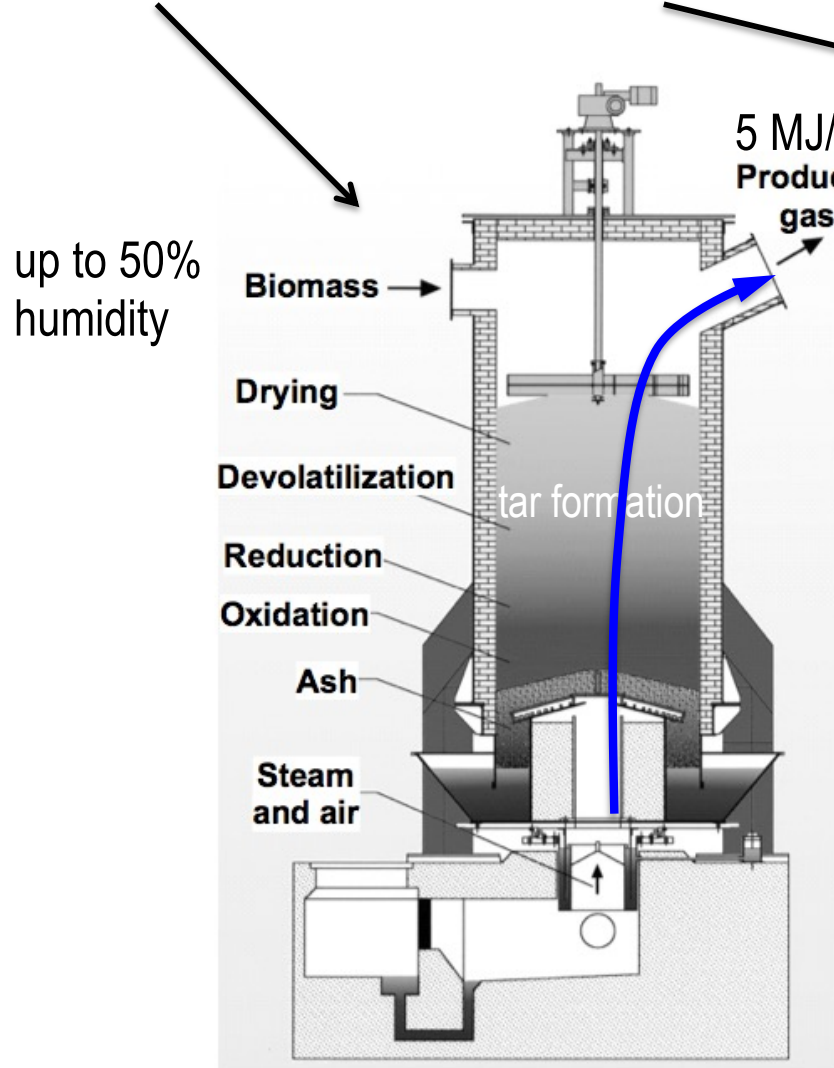
4. Stages

- single
- two

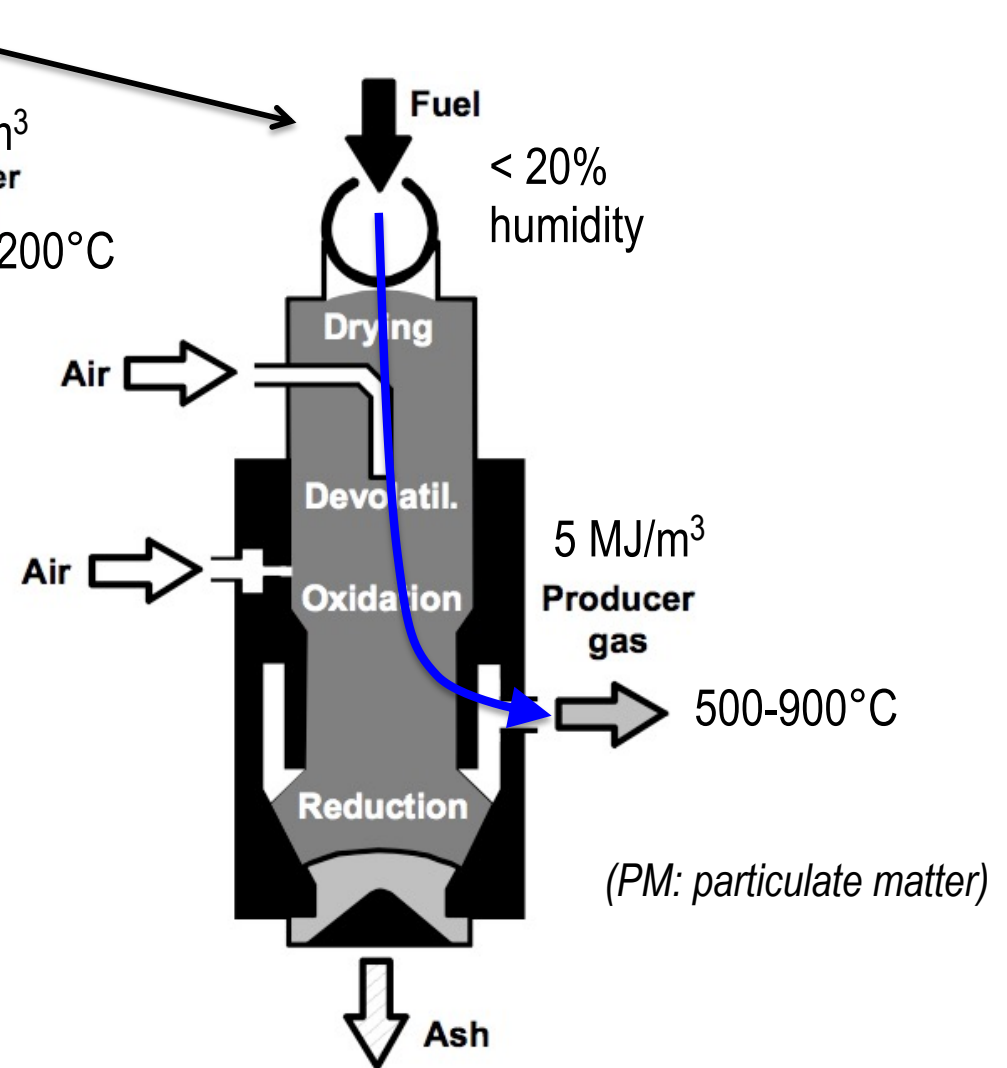
<http://www.youtube.com/watch?v=GkHKXz3VaFg>

Updraft / Downdraft (fixed beds)

F. Nagel, PhD thesis, PSI



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 ($< 6\text{g/m}^3$) – all cracked at high T
 higher PM (no filtering by wood)
 2 MW_{th} max (limited heat transfer from the sides for thermal homogenisation)

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

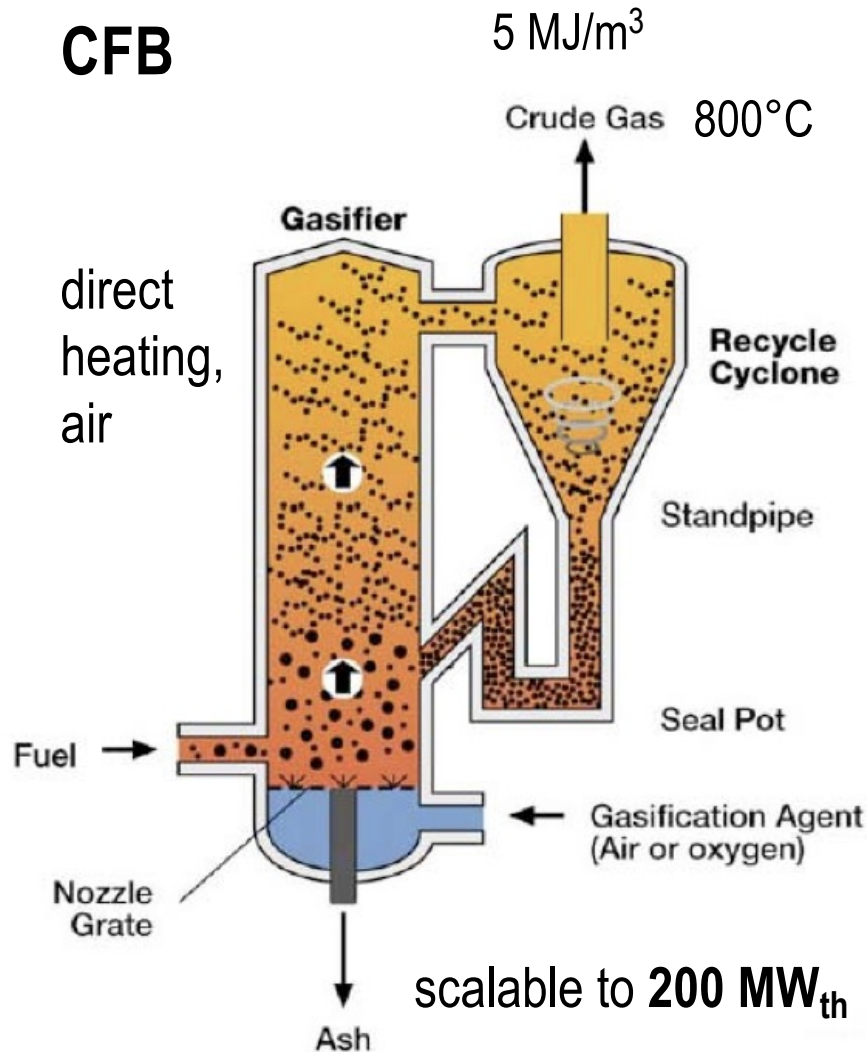
- **Down:**

- the downward flow entrains the volatiles (**tars**) into the hottest combustion zone where these are cracked to CO and H₂
- limited in power size; more critical thermal management

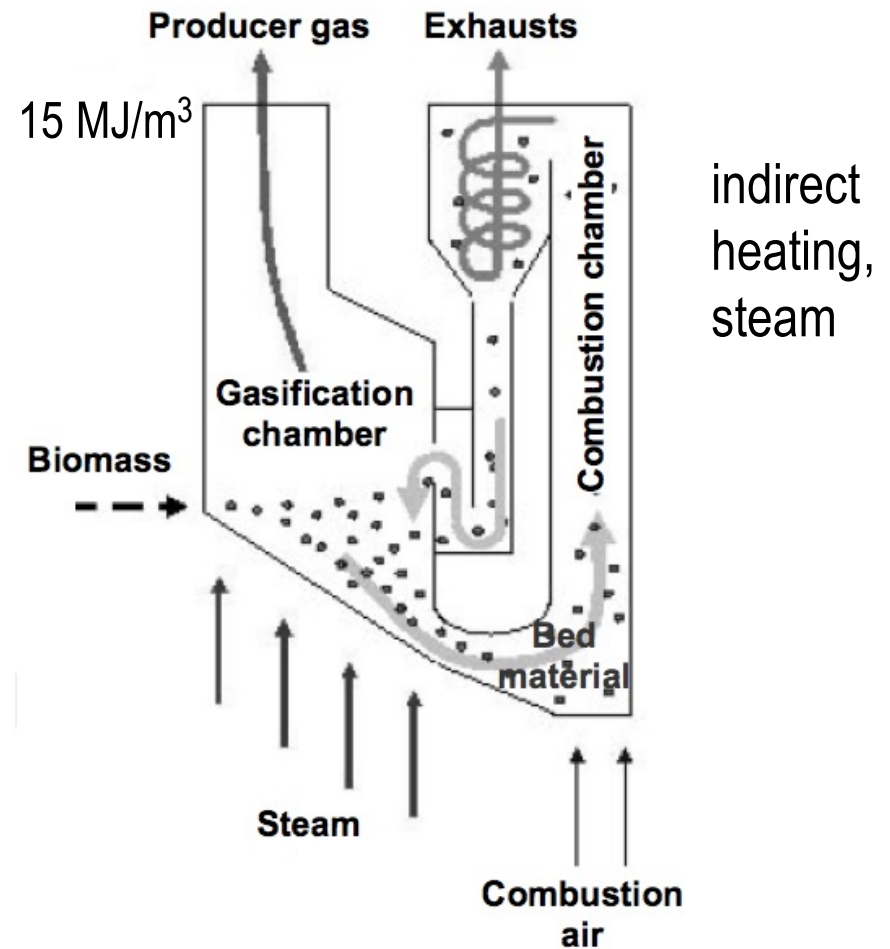
Circulating fluidised beds (CFB)

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

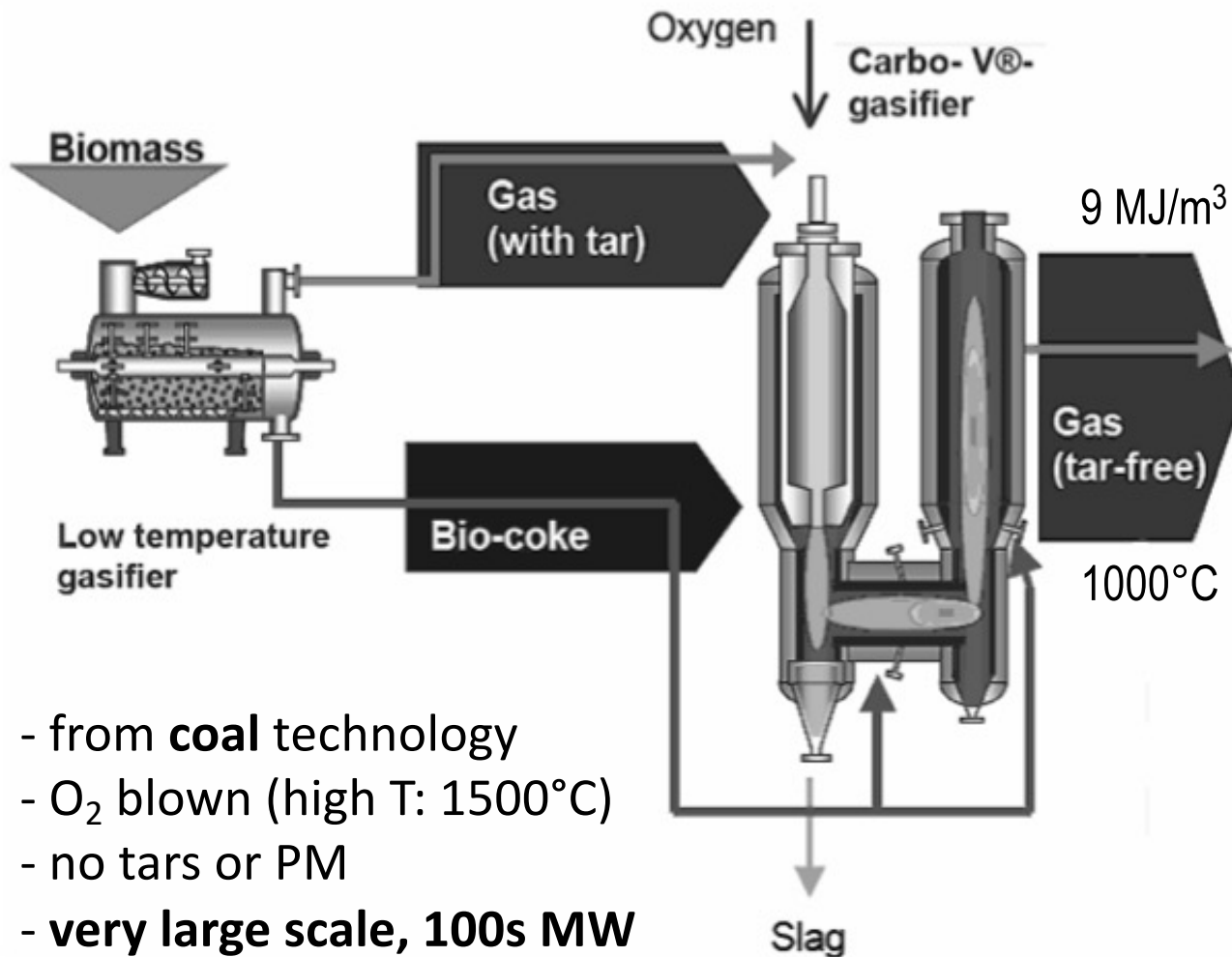
CFB



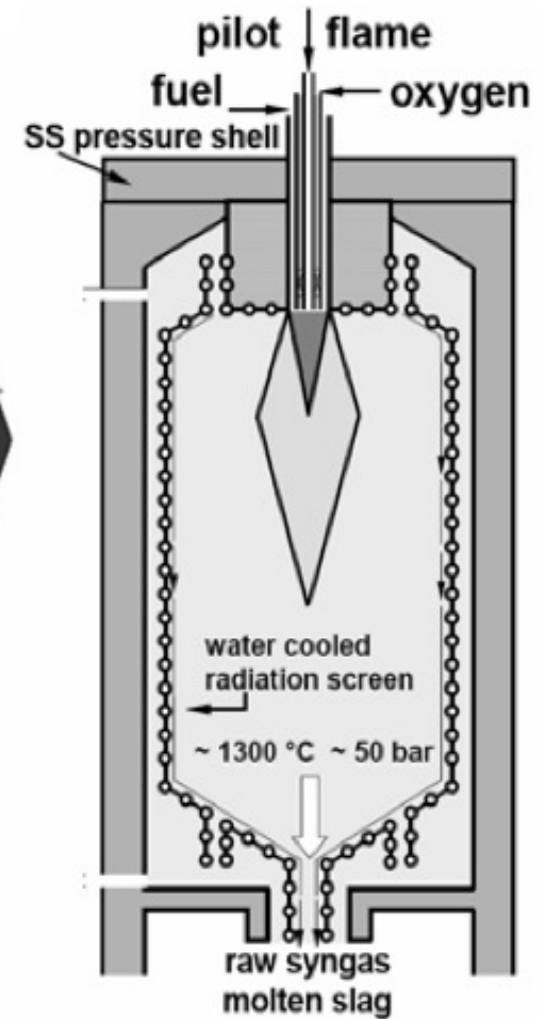
FICFB (Fast Internally CFB)



Entrained flow gasifiers



- from **coal** technology
- O₂ blown (high T: 1500°C)
- no tars or PM
- **very large scale, 100s MW**



F. Nagel, PhD thesis, PSI

Gasification comparison

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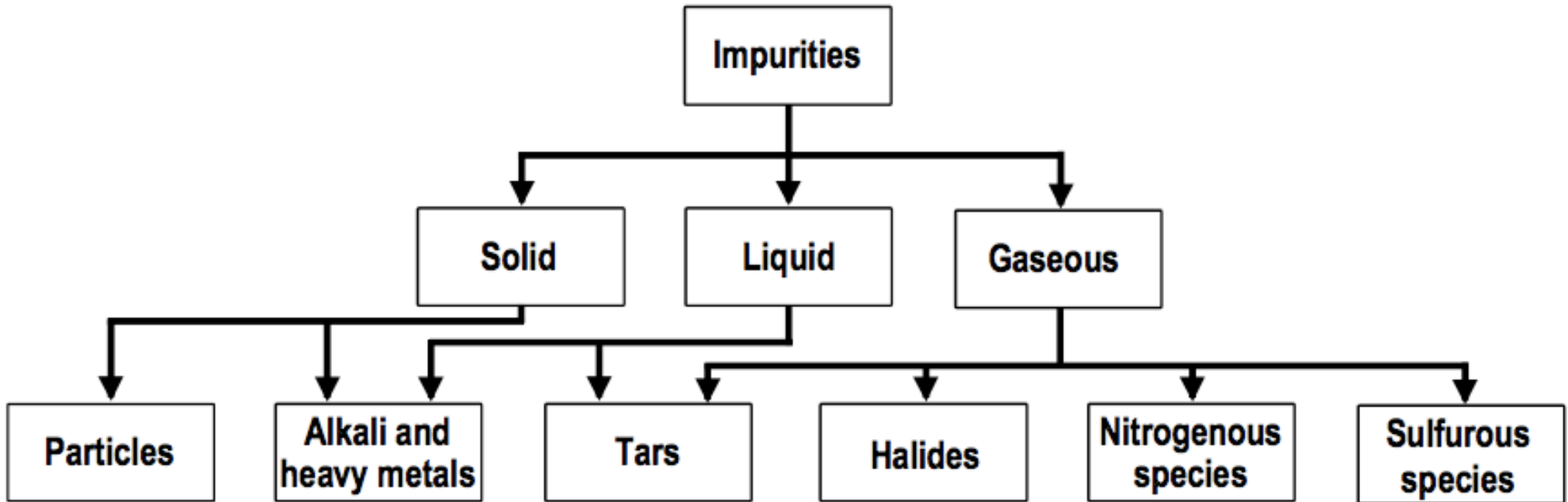
	Unit	Updraft	Down-draft	Fluid. Bed	Circul. FB	Entrain. flow
Gasification agent	[-]	Air	Air	Air/O ₂ /H ₂ O	H ₂ O	O ₂
H ₂	[mol-%]	10-14	15-21	15-22	17-36	29-40
CO		15-20	10-22	13-15	36-51	39-45
CO ₂		8-10	11-13	13-15	7-15	18-20
CH ₄		2-3	1-5	2-4	0.1-0.6	0.05-0.1
C ₂		-	0.5-2	-	1.4-7.5	-
N ₂		53-65	37-63	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 oxygenated	aromatic	oxygenated and aromatic	oxygenated 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	homogeneous	homogeneous	homogeneous	Suspension
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 m³ producer gas of :
18% CO / 16 % H₂ / 2 % CH₄ / 14% CO₂ / 50% N₂
(LHV: 305 kJ/mole (CO); 241 kJ/mole (H₂); 800 kJ/mole (CH₄))
- What is the energy content per m³ of producer gas? How does this compare to natural gas?
- What is the '*cold gas efficiency*' (=energy balance) of the process?

Impurities from wood



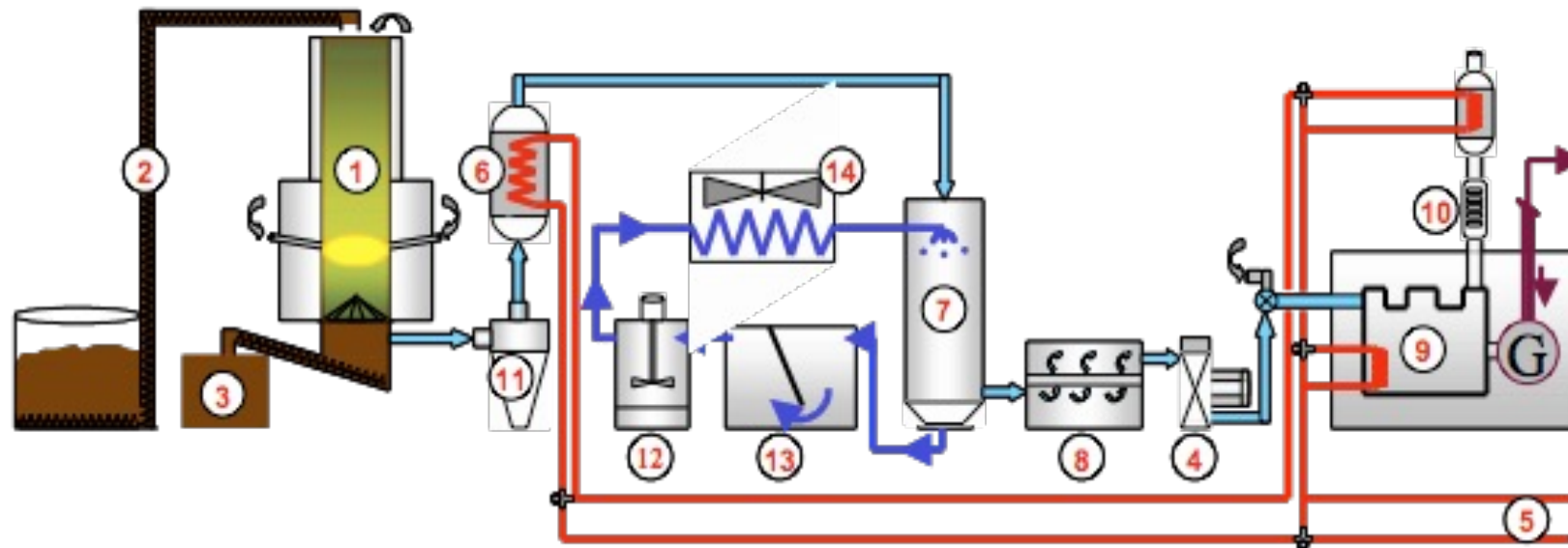
- this is a complex issue for downstream *engines, turbines,...*
- tars = fuel (avoid condensation, but also fouling)
- cleaning needed (hot or cold)

Wood gasification plant

COMPOSANTS

100-200 kW_{th}

complex gas cleaning

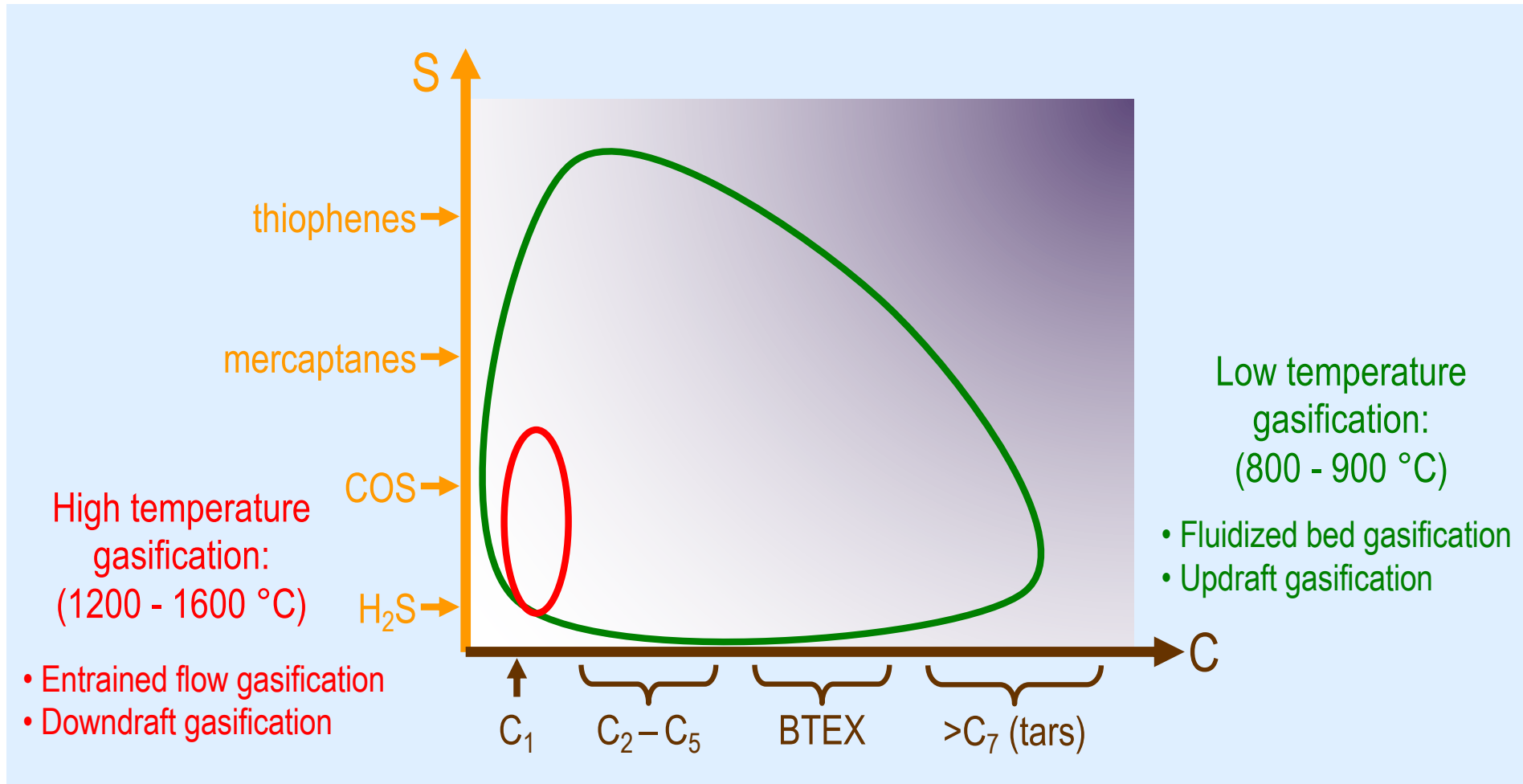


Légende :

- | | | |
|---------------------------|--------------------------------|-------------------------|
| 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, H₂O)
- 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 H₂S
- absorb H₂S 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 μ GC (24/24 h)
- Automatic cell phone alarm in case setup is leaving prefixed operation window
- Remote control

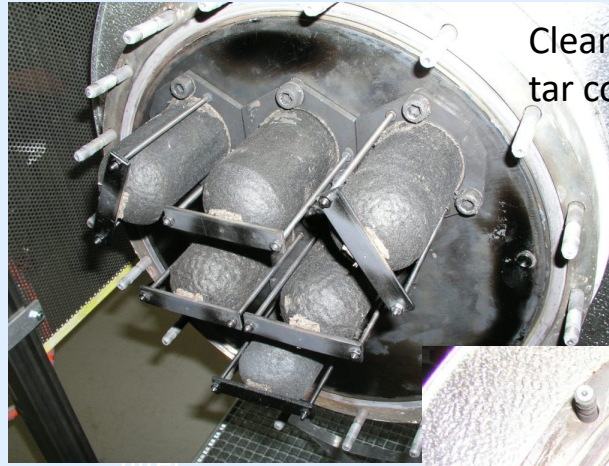
Hot gas cleaning (candle filter)

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 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)



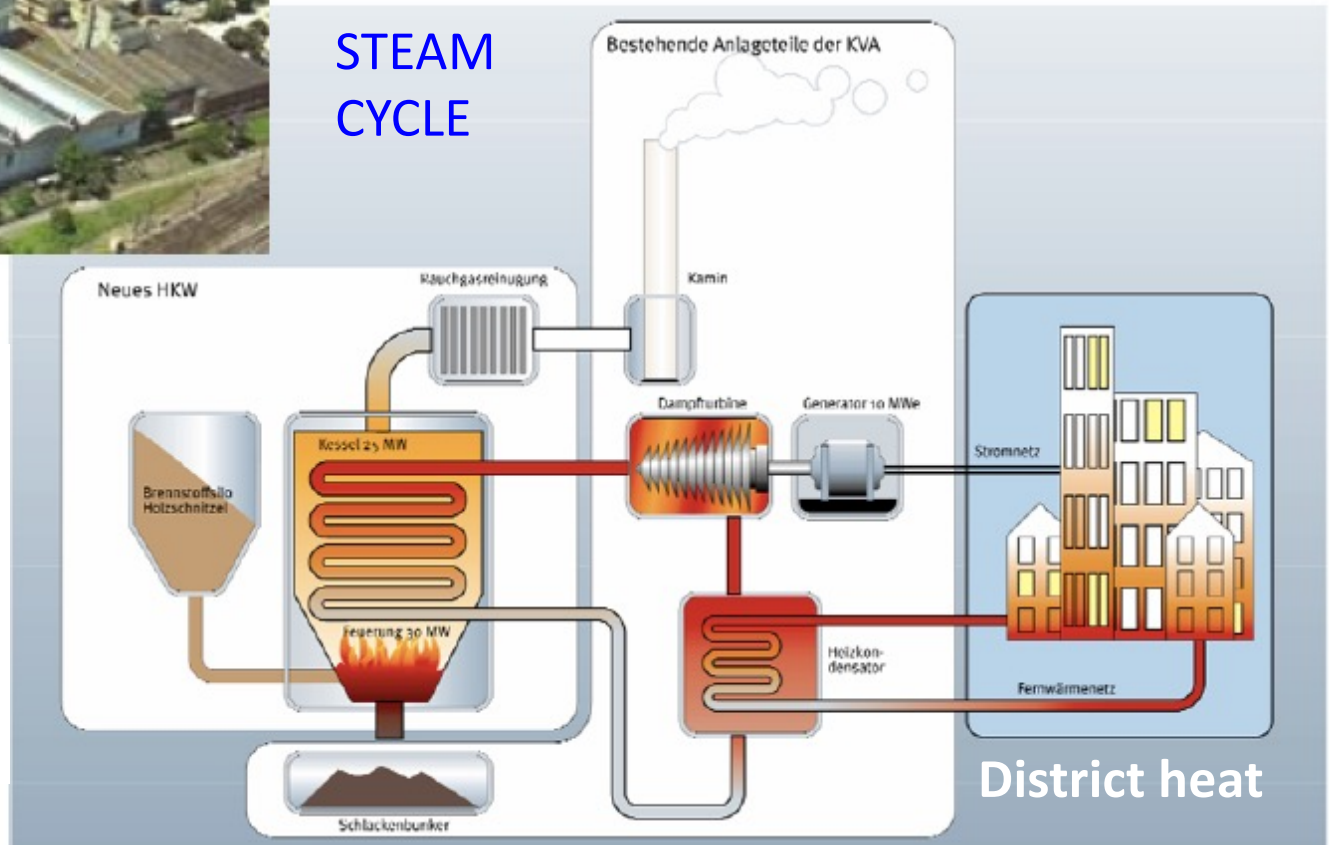
Basel (CH)

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30 MW_{th}, **4 MW_e**, 21 MW_{heat}
 since 2008
 170'000 m³/yr = 43'000 t/yr

Zürich (CH)

42 MW_{th},
11 MW_e, 28 MW_{heat}
 since 2010
 265'000 m³/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)**

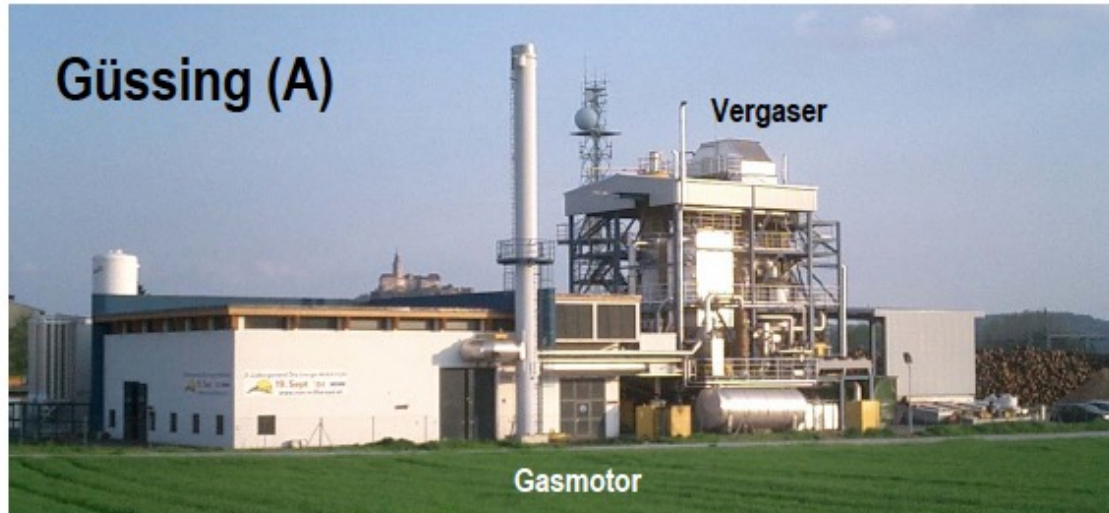
started in 1998 (with biomass: 2006)

100'000 t/yr wood



Cogeneration / IGCC

S. Biollaz, PSI-TPE



Cogeneration, Güssing (AUT)

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

Since 2002; 50'000 h operation

15'000 t/yr wood

IGCC Värnamo demo (SWE)

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

1996-1999

7000 h operation



Wood IGCC

'BIG-CC' : Biomass Integrated Gasification
combined cycle

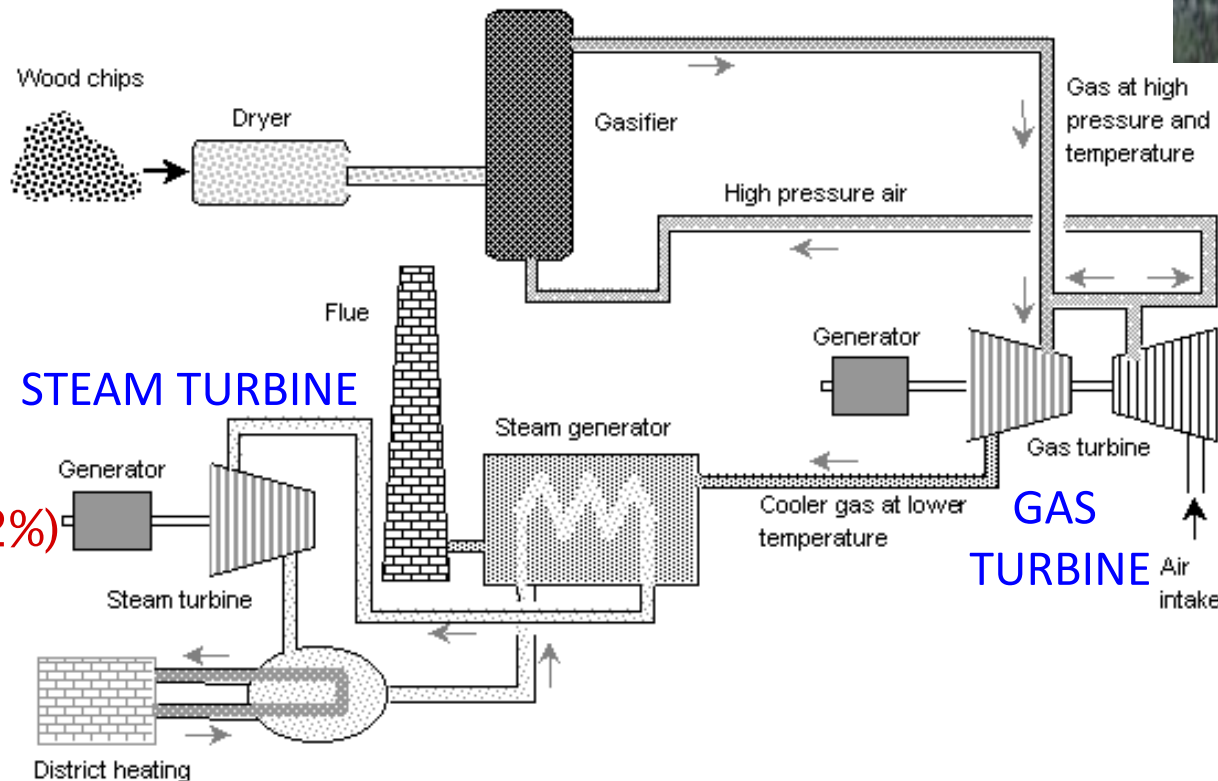


Varnamo (SWE)

Fuel
18.3 MW

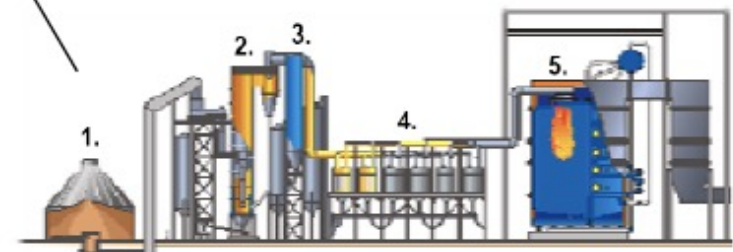
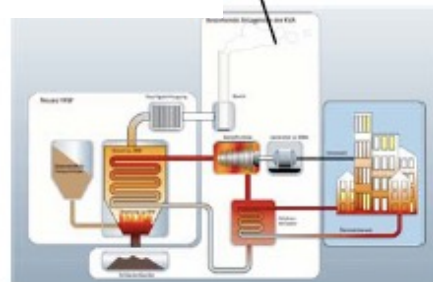
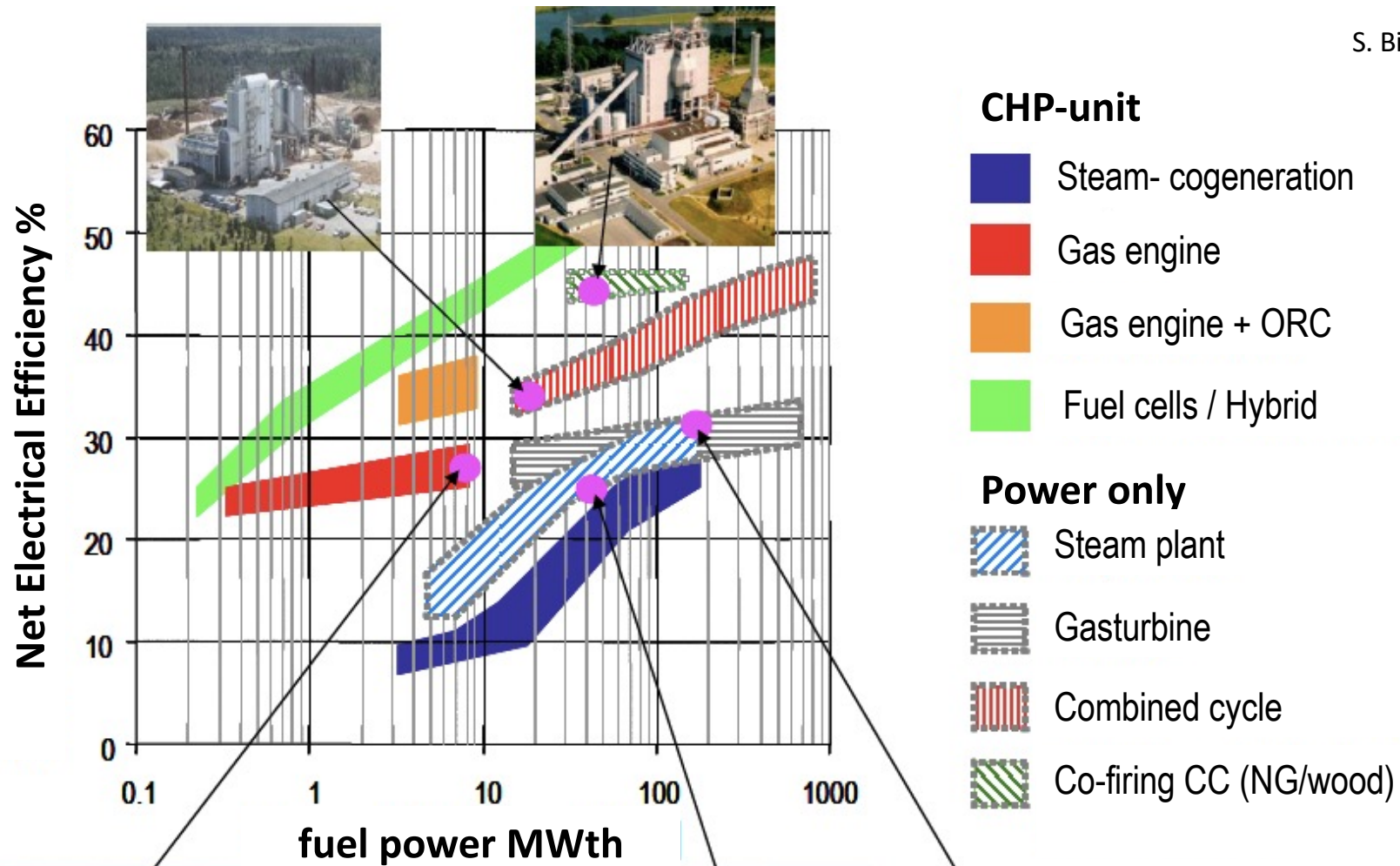
Electricity
6 MWe (32%)

Heat
9 MW



Electrical efficiencies from wood

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)

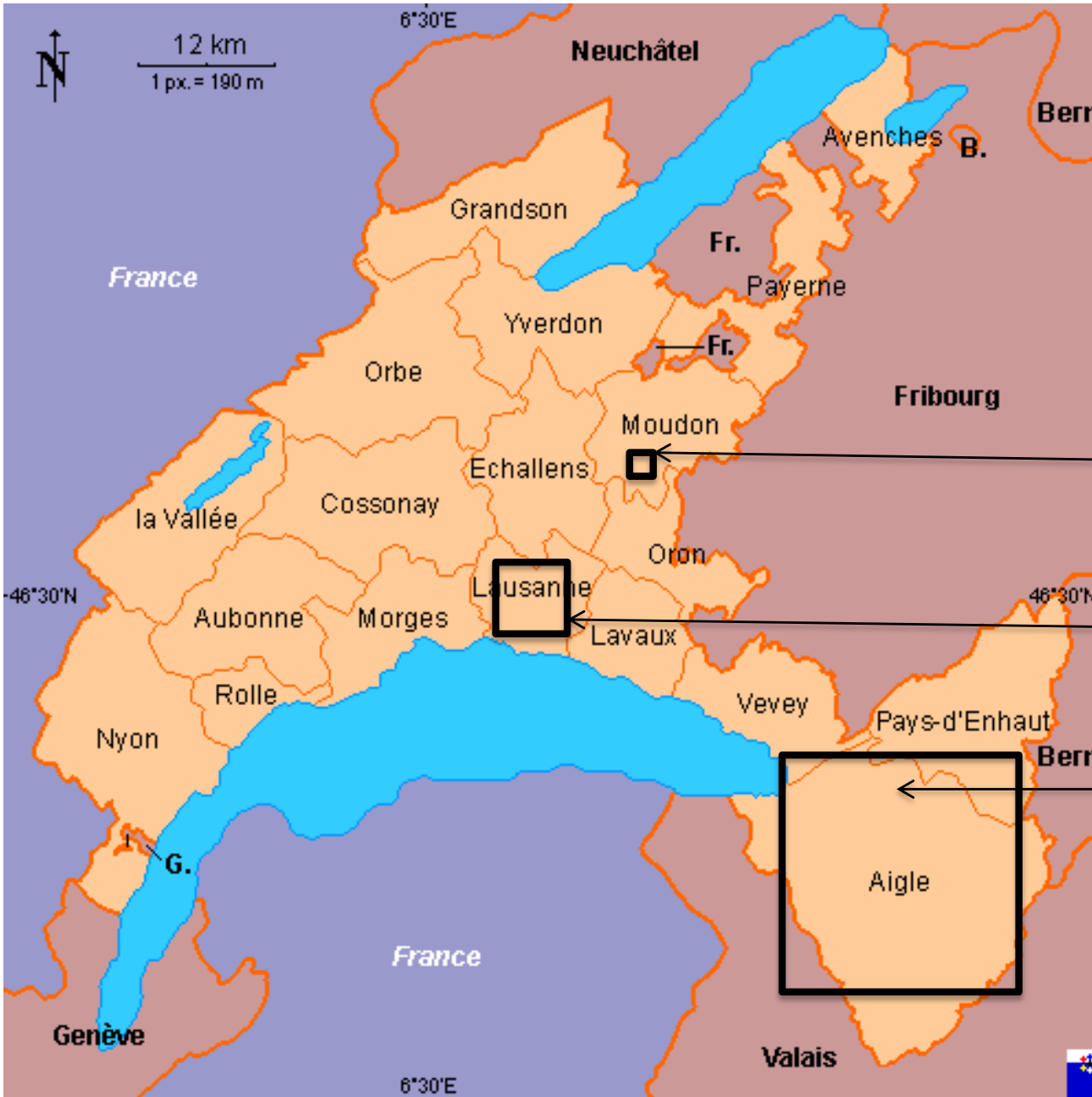
Possible energy crops : herbaceous, woody, aquatic

Lignocellulosic energy crop plantations (woods, grasses)

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

Climate	Examples	
cold	bamboo, elephant grass	
cold-temperate	willows, poplars	
warm-temperate	eucaliptus, robinia/acacia, mimosa, thistle (<i>cynara</i> (<i>fr.:</i> <i>cardon</i>), 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)

$$1 \text{ MW}_{el} = 4 \text{ km}^2 = 2 \times 2 \text{ km}$$

1 MW_{el}

10 MW_{el}

100 MW_{el}

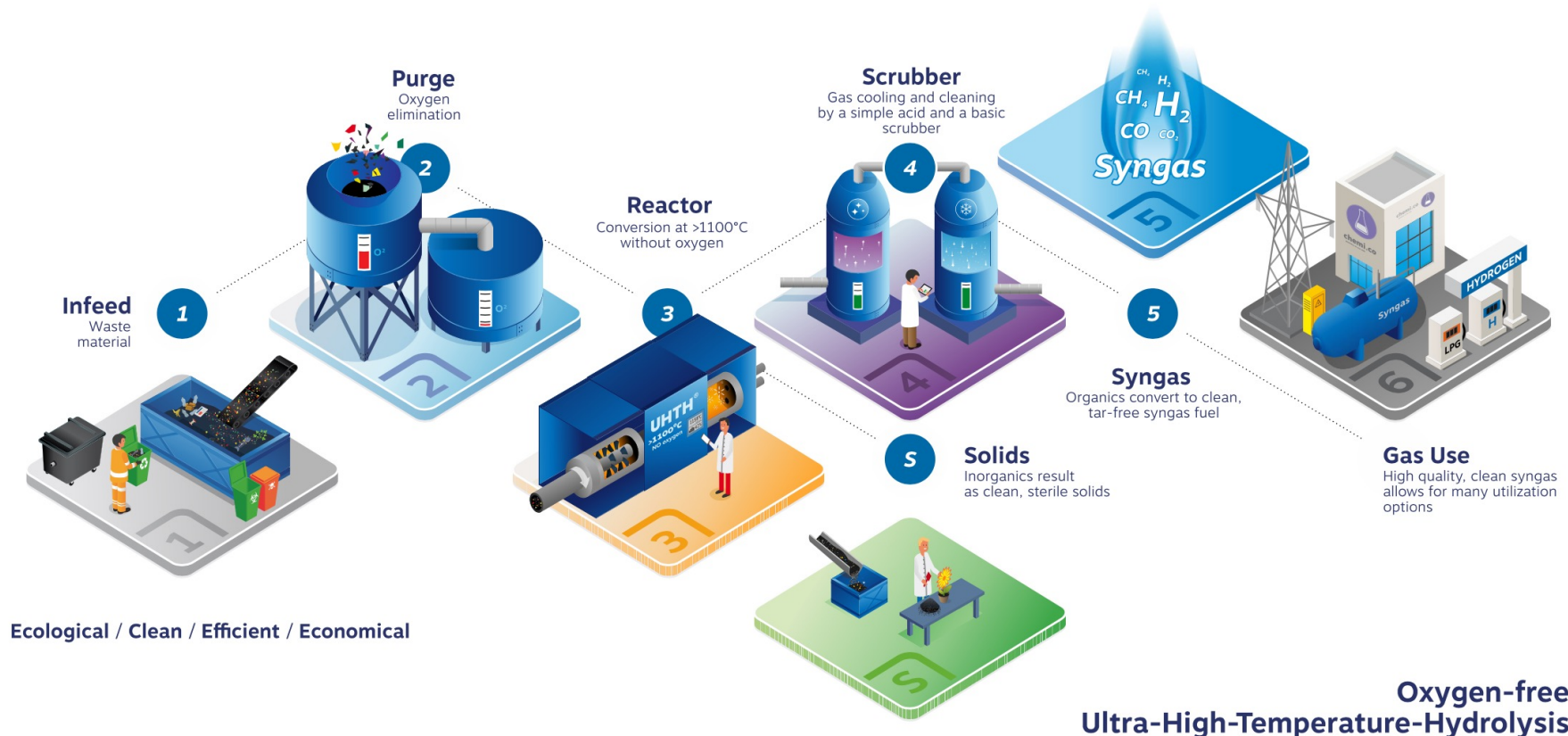
4000 km² would be required for a 1 GW_e plant. Biomass plant scale is therefore typically of 10 MW_{el}.

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 ≈ 6 GJ
 - at 82 \$/barrel, oil cost is **14 \$ / GJ** (0.5 \$/L)
- natural gas : **22 \$ / GJ** (8 ct / kWh)
- coal price: 112 \$ / tonne (~25 GJ) → **5 \$ / GJ**

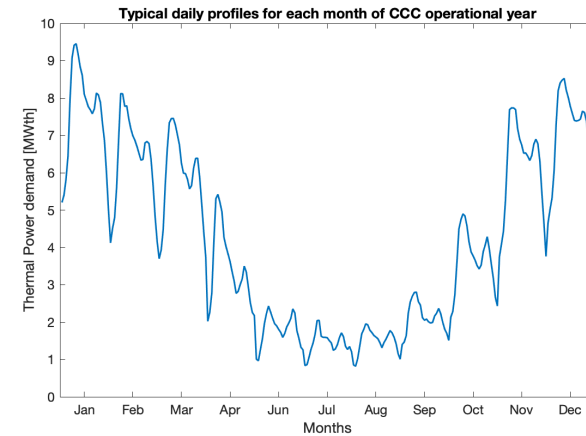
Clean Carbon Conversion (CCC) waste gasification technology

- Ultra-High-Temperature-Hydrolysis (>1100°C)
- High variety of infeed ('all solid wastes')
- Automation of process
- **Tar-free scrubbed syngas for**
 - Co-generation
 - H₂ extraction
 - CH₄ extraction



Application example

Dynamic heat demand profile



Energy balance :

