King Saud University
Sustainable Energy Technologies
Center (SET)

BIOMASS GROUP

Principals of Biomass Gasification

by Dr. Salim Mokraoui
PhD Chemical Eng.
MS. Mechanical Eng.

E-mail: smokraoui@ksu.edu.sa
Tel: 014676832

Outline

- **Introduction**

1. What is Biomass Energy
2. Potential of Biomass energy
3. Main Technologies routes

- **Principals of gasification**

1. Overview and principals
2. Gasification processes
3. Gasifiers performance

- **Design considerations of Gasification systems**

1. Basic data
2. Performance parameters

- **Applications related to gasification**

What is Biomass Energy

- **Biomass** is any organic matter, especially plant matter, which can be converted to fuel and is therefore regarded as a potential energy source.
- **Bioenergy** is the energy which is retrieved from biomass
- Biomass is an extremely important energy source, available nearly everywhere
- Biomass encompasses a large variety of materials, including wood from various sources, agricultural and industrial residues, and animal and human waste
- Two forms of biomass

Raw: forestry products, grasses, crops, animal manure, and aquatic products (seaweed)

Secondary: materials that undergone significant changes from raw biomass. Paper, cardboard, cotton, natural rubber products, and used cooking oils.

What is Biomass Energy

Biomass Composition

Biomass is composed from carbohydrate polymers (cellulose and hemicellulose), aromatic polymers (Lignin), proteins and fats (lipids)

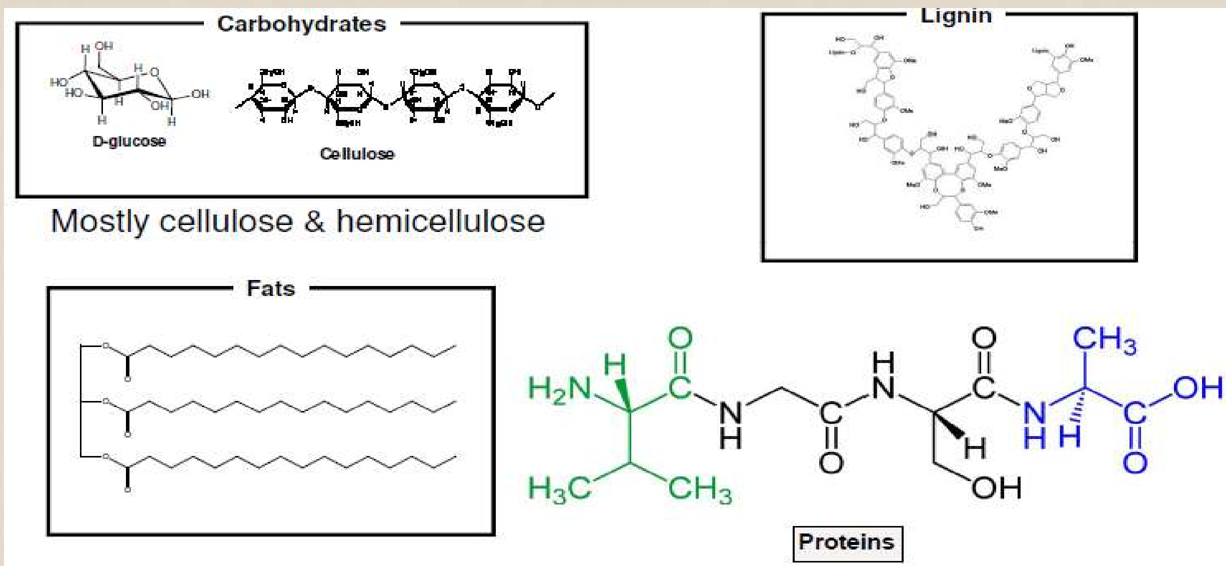
Cellulose ($C_6H_{10}O_5$) is the most important structural component of the primary cell wall of green plants and most abundant organic polymer on earth

Hemicellulose present with cellulose in almost all plant cell walls

Cellulose is crystalline, strong and resistant to decomposition in presence of heat, but hemicellulose has a little strength in front of heat

Unique characteristic of biomass as the only renewable and carbon based resource, makes it more attractive for energy purposes

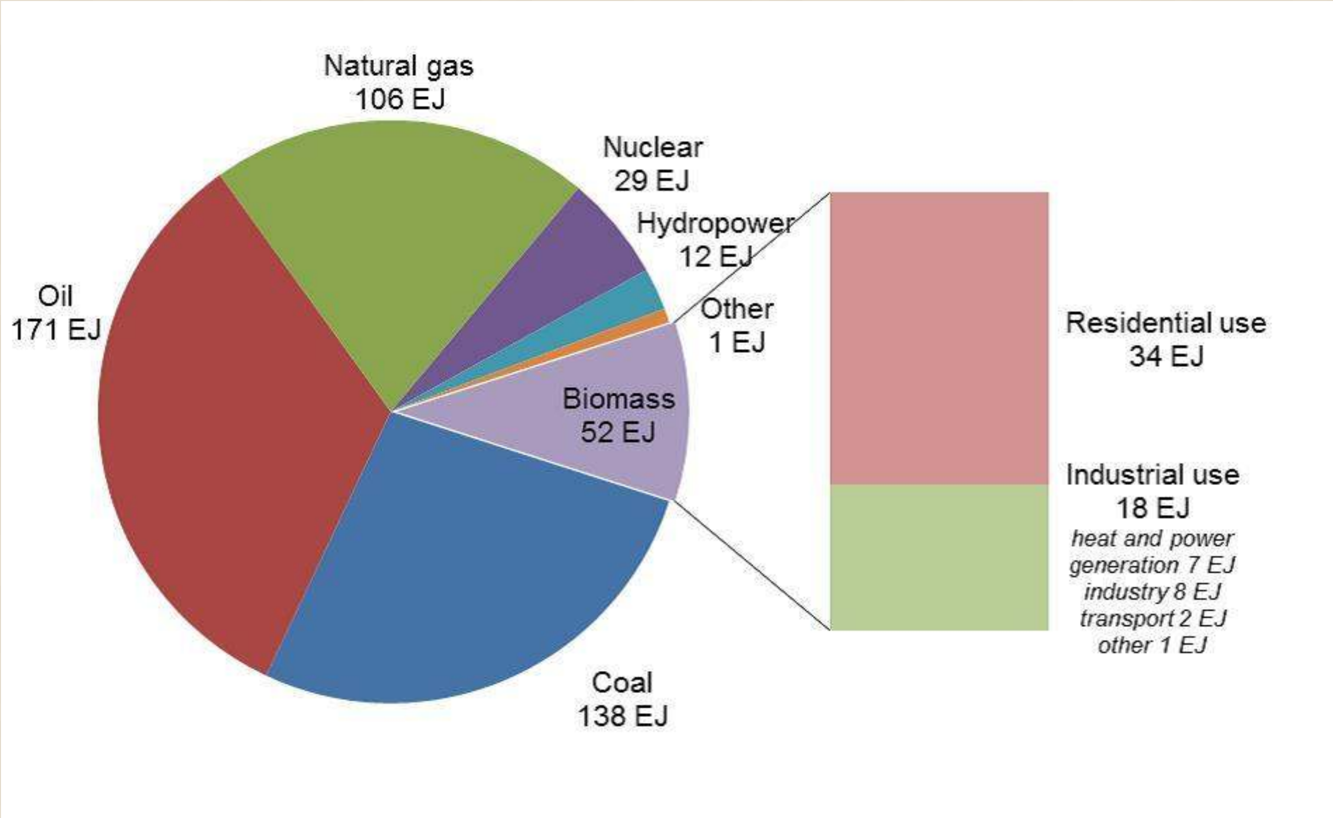
Divided into wet and dry biomass



Biomass Composition

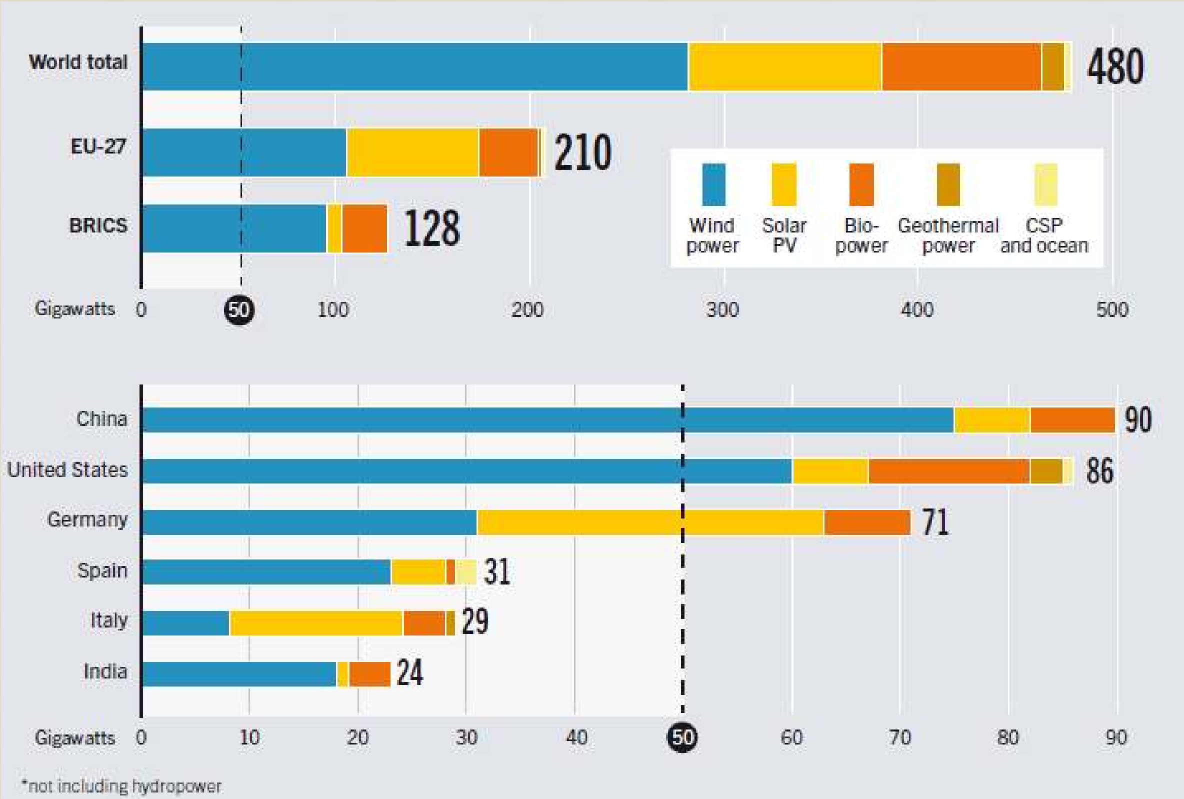
Biomass	Lignin (%)	Cellulose (%)	Hemicellulose (%)
Softwood	27 – 30	35 – 42	20 – 30
Hardwood	20 – 25	40 – 50	20 – 25
Wheat straw	15 – 20	30 – 43	20 – 27
Switchgrass	5 – 20	30 – 50	10 – 40
Animal manure	5 – 8	10 - 20	15 – 22
Newspaper	18 – 30	40 – 55	25 – 40
Sorted refuse (MSW)	20	60	20

Potential of Biomass energy



Biomass provides more than 10 % of Global energy use (International Energy Agency, 2013)

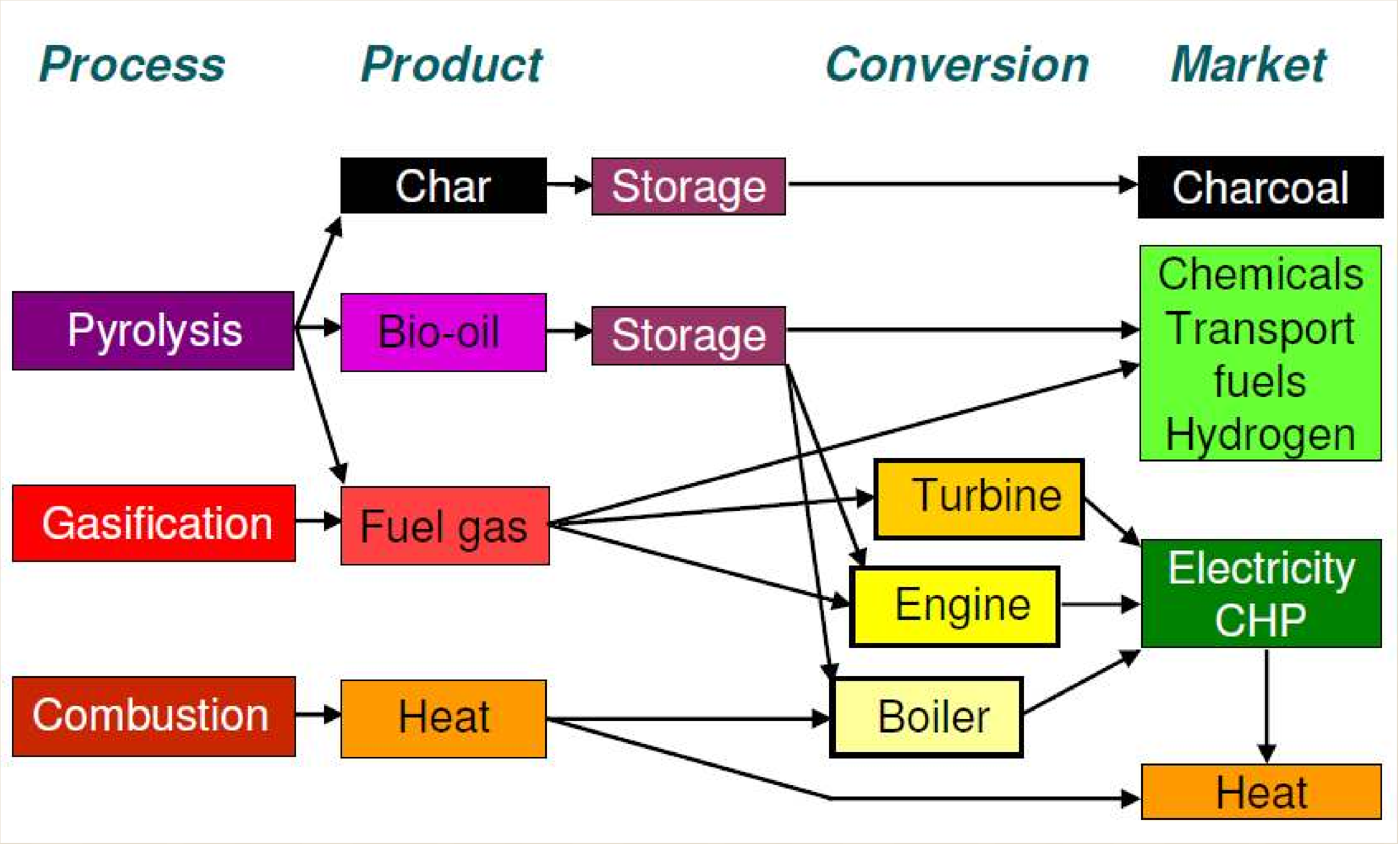
Potential of Biomass energy



Renewable and Bio-Power Capacities in World
(International Energy Agency, 2012*)

Main technologies routes

Thermochemical conversion options



Potential of Biomass energy

Advantages:

- Biomass reduce the dependence on fossil fuels
- It provides an inexpensive and readily available source of energy, and chemicals
- It offers another major benefit to sustainability namely a pathway to manage municipal and agricultural waste
- Processing biomass materials for fuel reduce the environmental hazard
- Biomass provides an effective low Sulphur fuel.
- It has many derived products that may substitute those of plastics and other products
- It has many applications for remote area

Disadvantages:

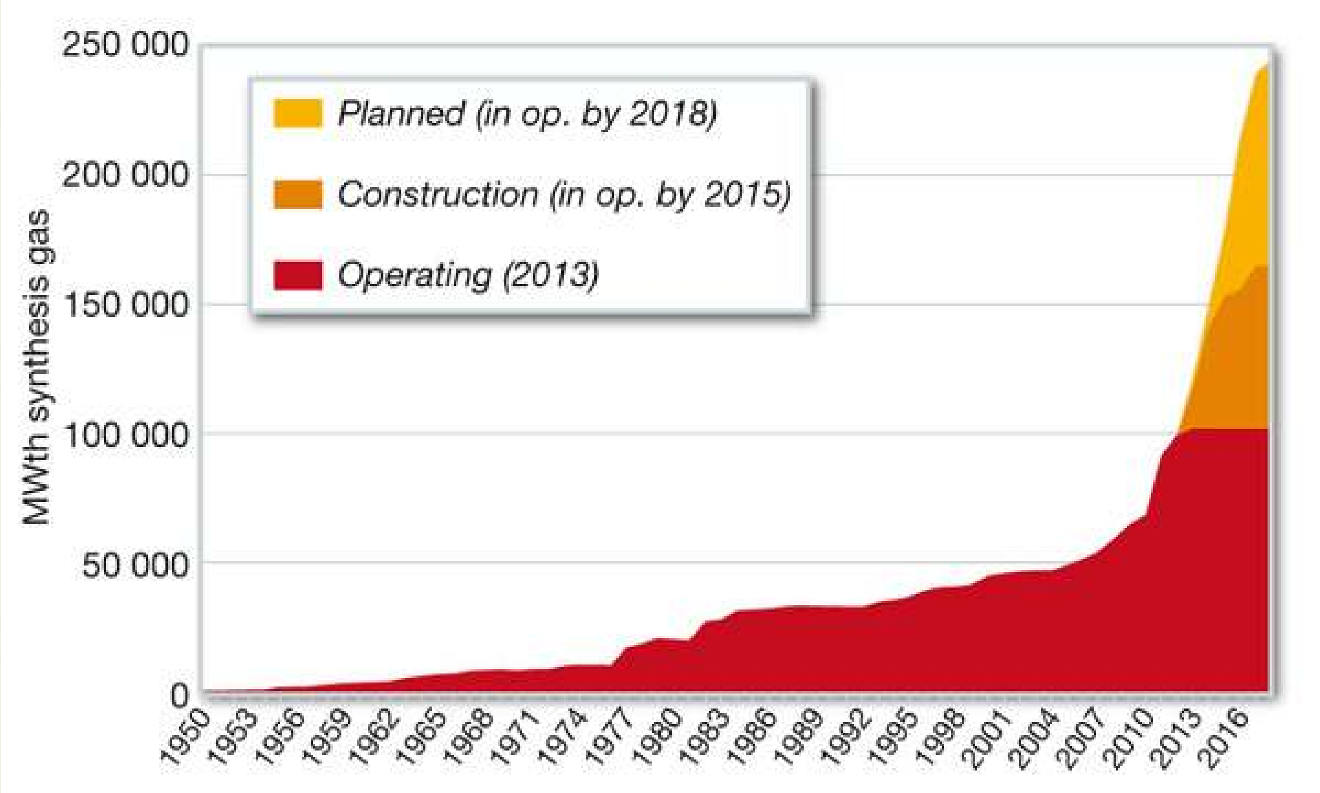
- Biomass has low energy content compared to coal and petroleum derived fuels
- Intensive cultivation may stress water resource and deplete soil nutrients
- It has high cost of transportation and pre-treatment

II- Principals of gasification

Overview and principals

- Gasification is a thermo-chemical process which converts biomass, into a combustible gas (mainly CO, H2, CH4 and other inert gases), through incomplete combustion-reduction
- Gasification is appealing because the produced gas can be used in IC engines or gas turbines, burned directly or used in the production of methanol or hydrogen
- The gasification process is well known since earlier 1800's for the production of town-gas for heating and lighting
- In the beginning of 1900's, compact gasifiers were used for automotive applications (gas engines)
- After becoming extinct (1^{st} and 2^{nd} wars), gasification raised again from 1940 and specifically after the oil crisis of 1970 to offer small scale wood-charcoal fueled power plants
- Currently, gasification is directed to the production of heat and electricity in advanced turbines based cogeneration units as well as to biofuels

Overview and principals

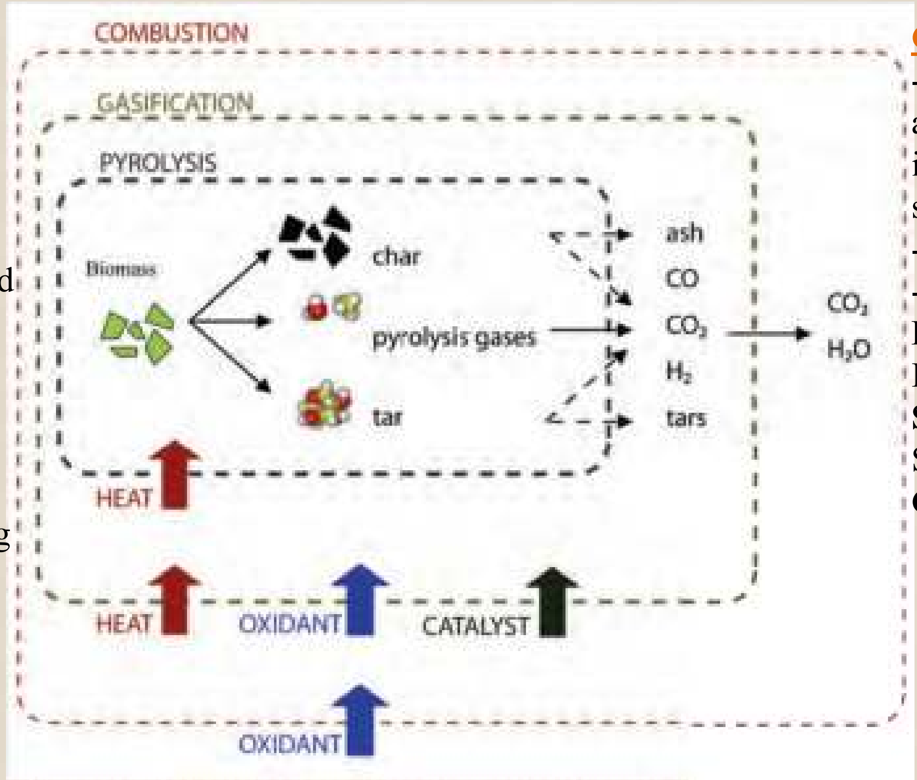


Cumulative worldwide gasification capacity (source: GTC database)

Overview and principals

Pyrolysis
- First step in combustion and gasification processes
- The feedstock is heated in a reactor in the absence of air or oxygen
- Moisture and other volatiles are released above 100 °C
- The pyrolysis process occurs mostly between 300 and 400 °C yielding:

Pyrolysis gas (CO, CO2, H2, CH4, light HC)
Synthetic oil (Tars) obtained after cooling of condensable vapors including water, methanol, heavy HC, etc.
Char (carbonaceous solid and other inert materials.



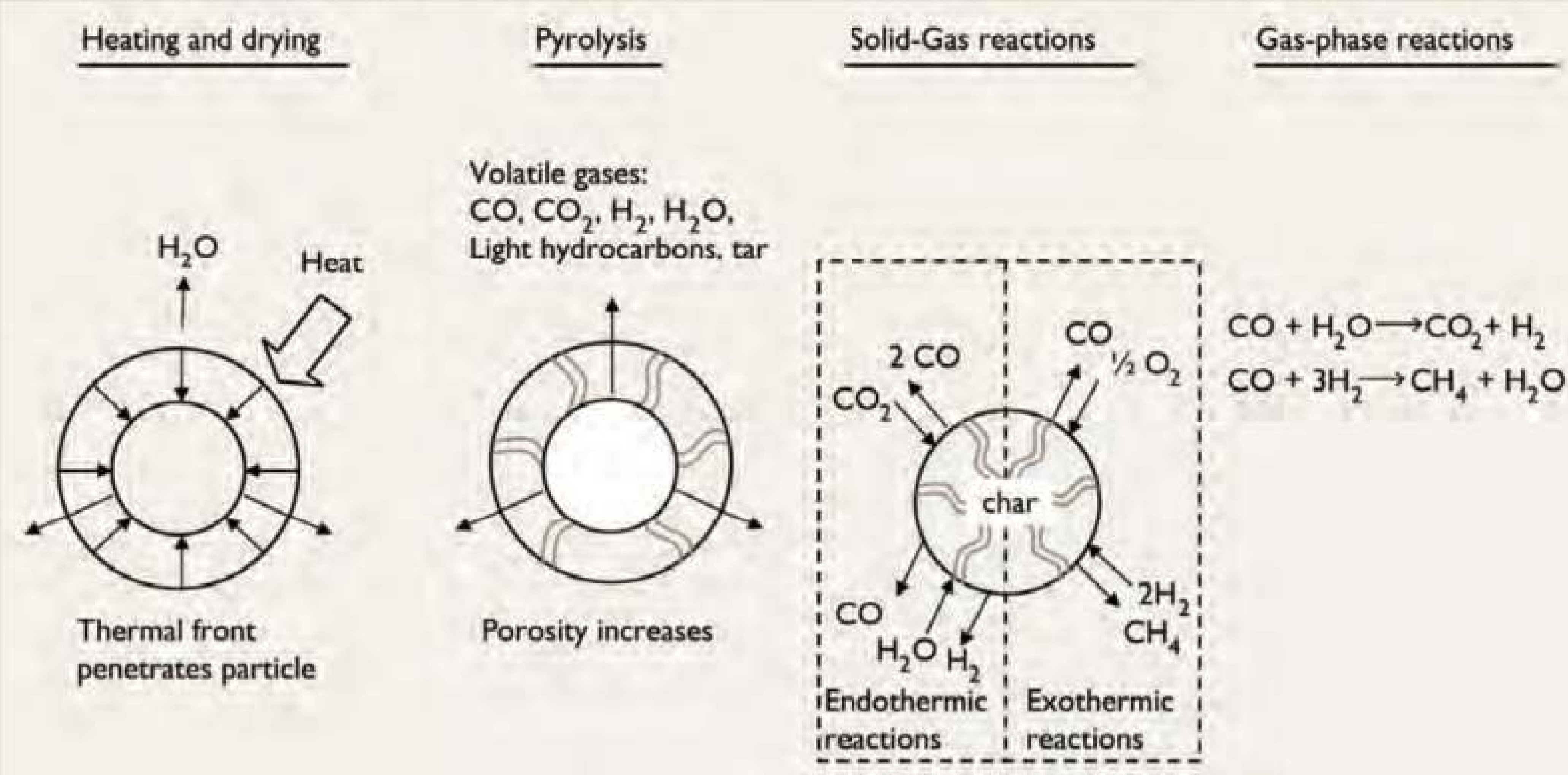
Gasification
- The conversion of solid fuel is carried out at higher temperatures – 750 to 1200 °C and in a controlled atmosphere with sub-stoichiometric conditions of oxidant.
- The process is mainly endothermic
- Gasification involves 4 steps:

Drying: moisture
Pyrolysis: volatiles, lights HC and tar
Solid-phase reaction: combustion of Solid carbon into CO, H_2 and CH_4
Gas phase reaction: reduction of CO

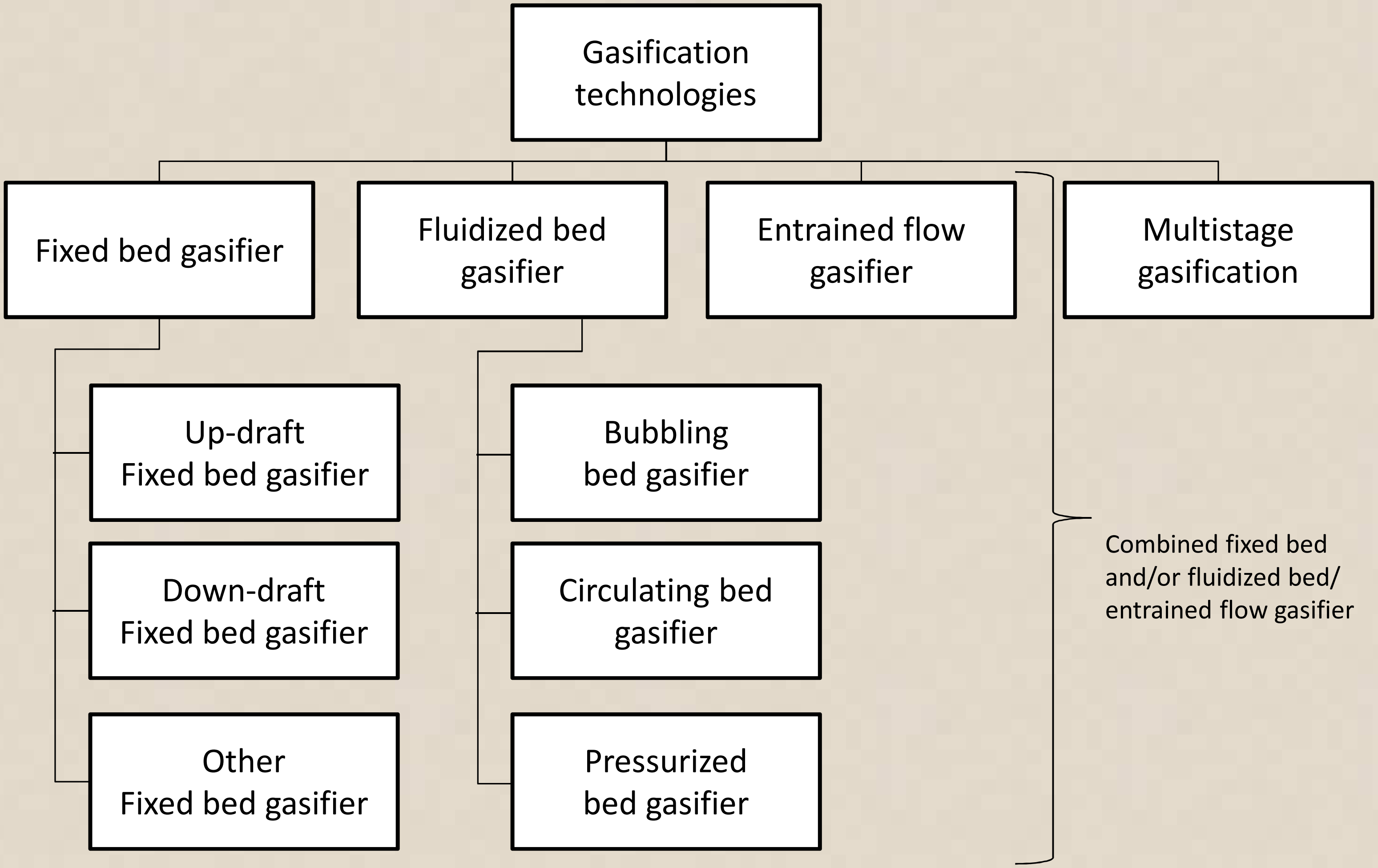
Combustion
- Rapid and complete oxidation of the solid fuel
- Main products: CO_2 and water
- High temperatures over 1200 °C

II- Principals of gasification

Overview and principals



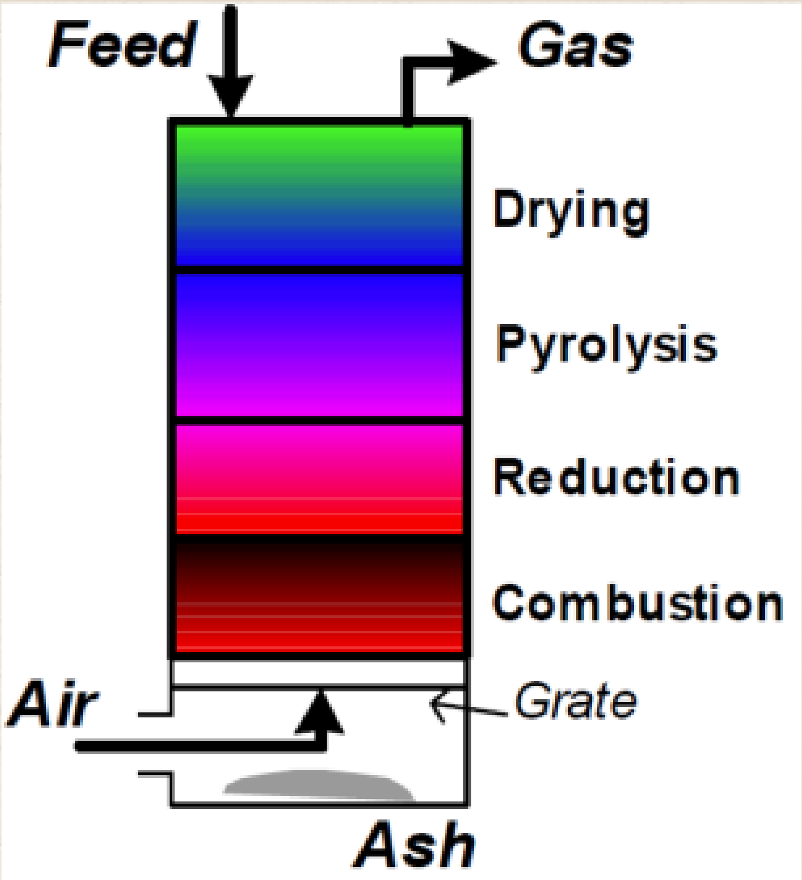
Gasification processes



Gasification processes

Fixed bed gasifiers

Updraft Gasifier



- **The gasification agent is added at the bottom, flowing in counter-current configuration with the feedstock, which is introduced in the top**
- **The fuel passes successively through drying and pyrolysis where it is decomposed into volatile gases and solid Char**
- **After pyrolysis has finished, the char is reduced by endothermic gasification reactions**
- **Combustion of char occurs near the grate and the hot combustion gases transfer heat to the rest of the process**
- **Char conversion is high, as the char reacts with oxygen as a last sub-process and char combustion reaction is faster than the char gasification reactions**

Gasification processes

Fixed bed gasifiers

Characteristics of Updraft Gasifiers

❑ **Updraft – Pros**

- **High char conversion, as the char combustion occurs at the last stage of the process**
- **The gasification efficiency is high due to high char conversion and due to that the gas exit temperature is relatively low (300-400°C).**
- **The gasifier construction is robust and relatively easy in operation**
- **Good fuel flexibility [size variation, moisture up to 60%]**

❑ **Updraft – Cons**

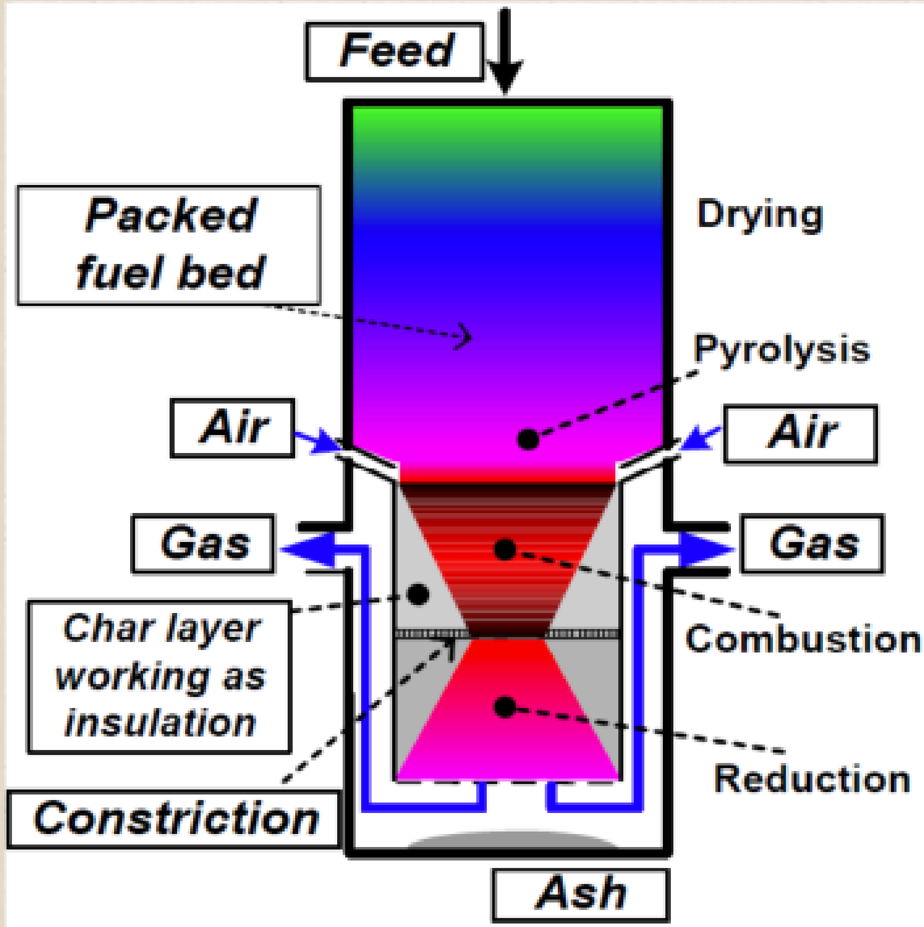
- **As pyrolysis takes place at rather low temperature, tars production are significant**
- **High capital cost**

Updraft gasifiers are suitable for moderate outputs [2 – 12 MW] such as direct combustion applications

Gasification processes

Fixed bed gasifiers

Downdraft Gasifier



- The gasification agent and feed stream are flowing in <u>co-current</u>
- In the oxidation zone, both pyrolysis gas and part of the char will burn
- Pyrolysis takes place above the combustion
- The <u>heat generated</u> from combustion is used for the char reduction reactions, pyrolysis and drying
- The pyrolysis temperature is high, Tars produced will to a large extent crack to light compounds

Gasification processes

Fixed bed gasifiers

Characteristics of Downdraft Gasifiers

❑ **Downdraft – Pros**

- **Very low tars, as the pyrolysis zone' temperature is high**
- **Good gas quality**
- **Modular design**
- **The gasifier construction and operation are simple**
- **Good fuel flexibility [size variation, moisture up to 60%]**

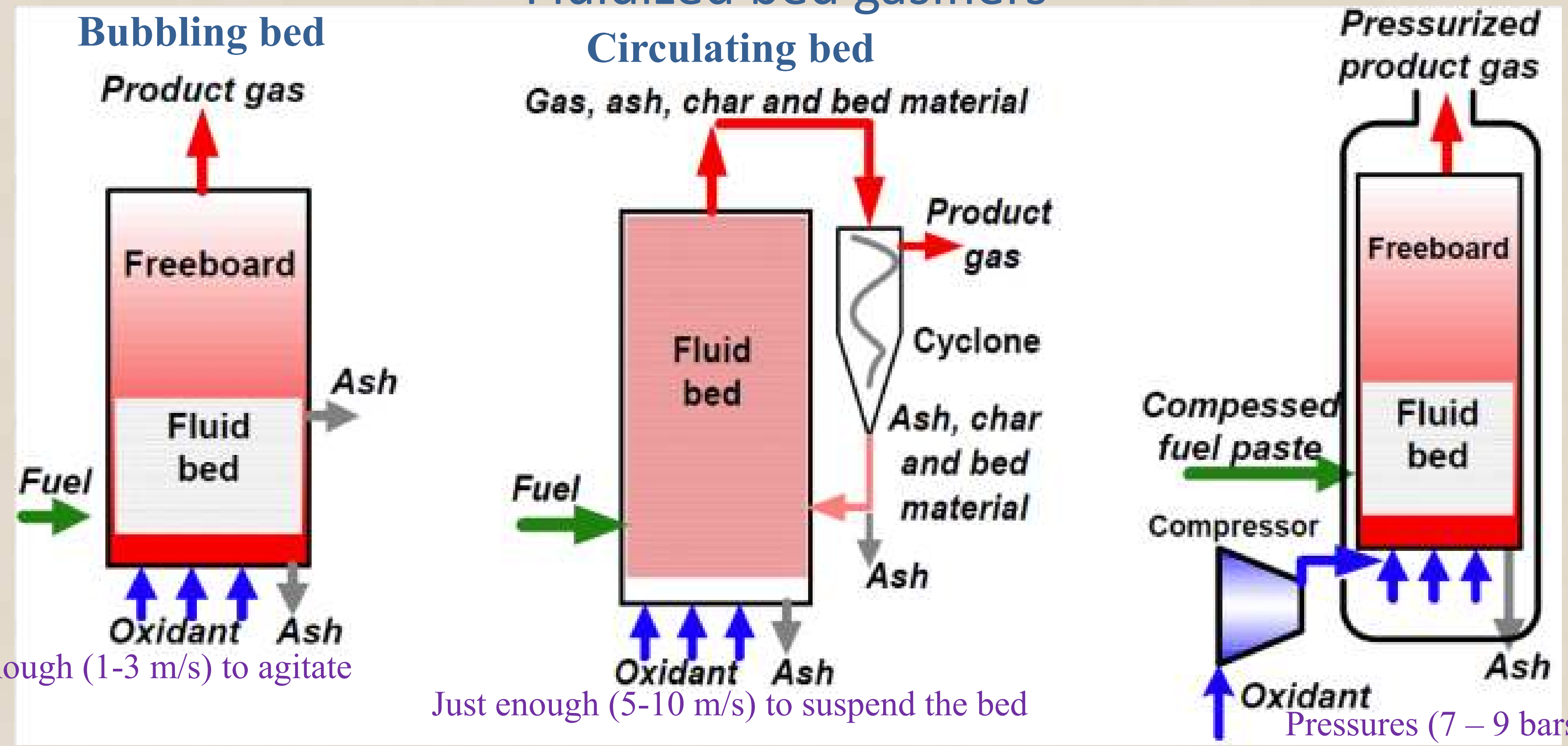
❑ **Downdraft – Cons**

- **Limited scalability [0.5 MW / 500 kg/h]**
- **Precise fuel requirement [specific size, shape and moisture]**

The product gas is suitable for IC-engine operation, for example powering small villages or industries

Gasification processes

Fluidized bed gasifiers



Just enough (1-3 m/s) to agitate

Just enough (5-10 m/s) to suspend the bed

Pressures (7 – 9 bars)

- A gas stream passes vertically upward through a bed of inert particulate material (sand) to form a **turbulent mixture of gas and solid**. Fuel is added at such a rate that it is only a few percent by weight of the bed inventory.
- No segregated regions of combustion, pyrolysis, and tar cracking exist. The violent stirring action makes the **bed uniform in temperature** and composition with the result that gasification occurs simultaneously at all locations in the bed

Gasification processes

Fluidized bed gasifiers

Characteristics of fluidized bed Gasifiers

- High char reactivity because of fast heating in pyrolysis region
- Oxidizer-fuel ratio can be changed; as a result the bed temperature can be controlled

❑ bubbling bed – Pros

- Flexible design
- Suitable for large outputs [>10 MW]
- Different fluidizing agent [steam, O_2, air or mix]

❑ bubbling bed – Cons

- High tars content
- Bed sintering problems

❑ CFB – Pros

- High fuel flexibility
- Suitable for large outputs [>10 MW]
- High electrical efficiency

❑ CFB – Cons

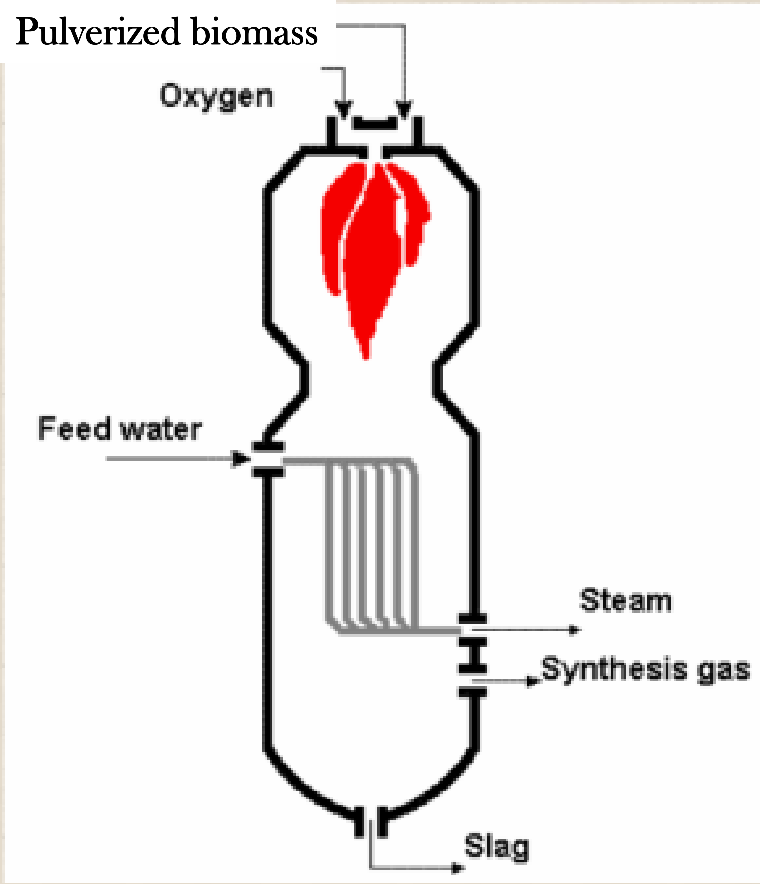
- Complex design
- High tars content
- High capital cost

Suitable for larger scale power plants (steam plants *or* combined gas turbine and steam plants)

Gasification processes

Entrained flow gasifiers

- Entrained flow reactors employ finely pulverized biomass and oxygen-steam as oxidizing agent in co-current flow
- High temperatures are achieved 1200 – 1500 ºC
- The flow is extremely turbulent and the residence time is short
- Commonly used for coal because finer particle sizes and higher temperatures can be achieved
- Tar and methane are not present in the product gas. High content of H_2
- Ash is removed as slag because the operating temperature is well above ash fusion temperature
- More practical for low grade coal and high coal throughput
- Application: synthesis gas for methanol production or power generation (IGCC)



Gasifiers Performance

Typical producer gas composition and heating value of some agricultural feedstock

Biomass fuel	Gasification method	Composition (% Volume)					Heating Value (MJ/m^3)
		CO	H_2	CH_4	CO_2	N_2	
Charcoal	Downdraft	28 - 31	5 - 10	1 - 2	1 - 2	55 - 60	4.60-5.65
Charcoal	Updraft	30	19.7	-	3.6	46	5.98
Wood (10-20% MC)	Downdraft	17 - 22	16 - 20	2 - 3	10 - 15	55 - 60	5.00 - 5.86
Wheat straw pellets	Downdraft	14 - 17	17 - 19	-	11 - 14	-	4.50
Coconut husks	Downdraft	16 - 20	17 - 19.5	-	10 - 15	-	5.80
Coconut shells	Downdraft	19 - 24	10 - 15	-	11 - 15	-	7.20
Pressed sugarcane	Downdraft	15 - 18	15 - 18	-	12 - 14	-	5.30
Corn cobs	Downdraft	18.6	16.5	6.4	-	-	6.29
Paddy husks pellets	Downdraft	16.1	9.6	0.95	-	-	3.25
Cotton stalks cubed	Downdraft	15.7	11.7	3.4	-	-	4.32

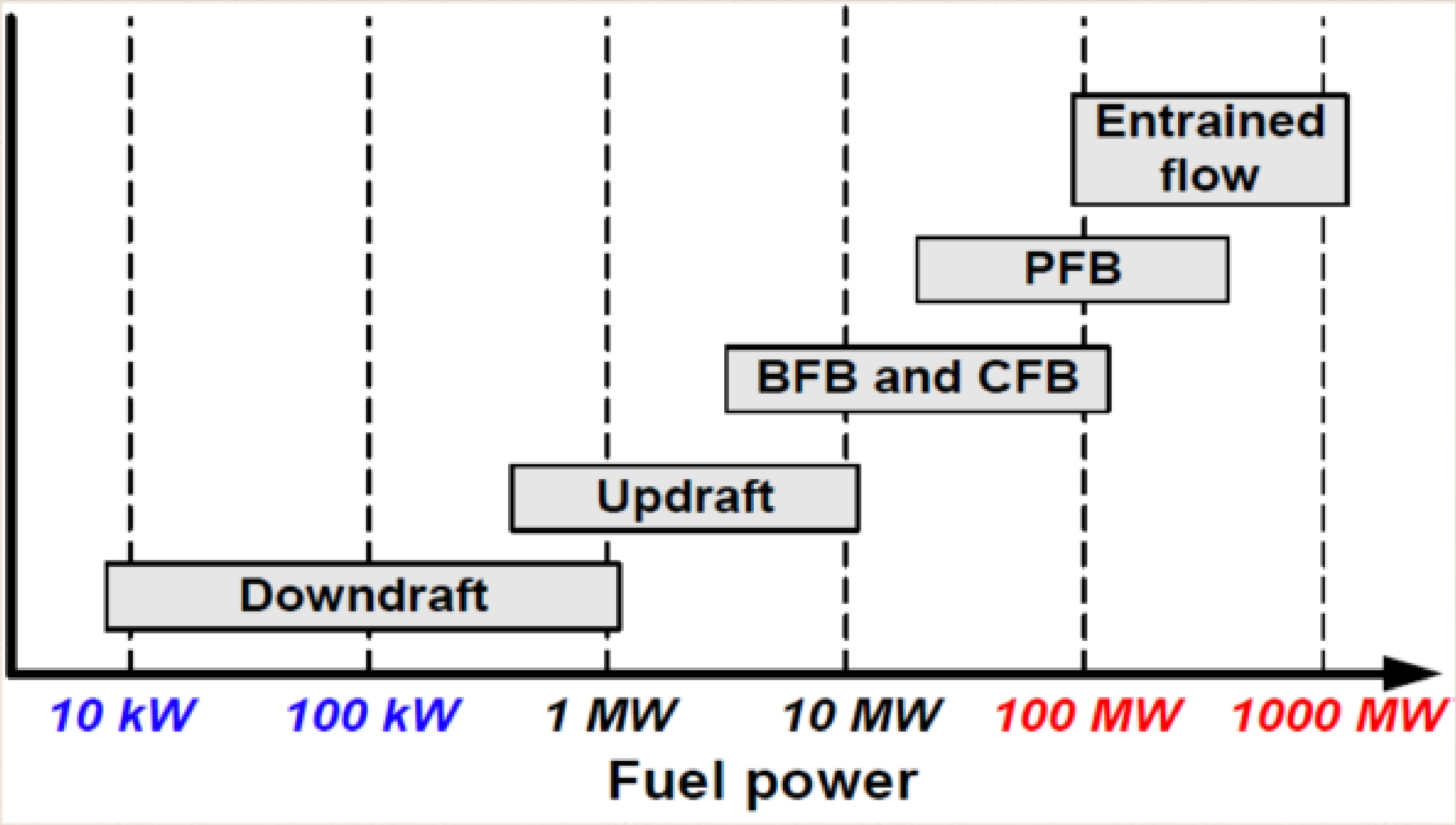
Gasifiers Performance

Characteristics and features

PARAMETERS	FIXED BED Up-draft	Down-draft	Cross flow	FLUID BED Bubbling	Circulating
Reaction temperature [C]	1000	1000	900	850	850
Gas temperature [C]	250	800	900	800	850
Throughput [t/h]	10	0.5	1	10	50
Electric power [MWe]	1 - 10	0.1 - 5	0.1 - 2	1 - 20	2 - 100
	GAS CHARACTERISTIC				
Tars content	v. high	v. low	v. high	medium	low
Particulates	av. high	medium	high	v. high	v. high
	FEEDSTOCK REQUIRAMENTS				
Mixing intensity	low	low	low	good	v. good
Limits for particle size	some	some	some	specific	specific
Moisture content	any	limited	limited	limited	limited
Fuel flexibility	no effect	low effect	low effect	strong	strong
	DEVELOPMENT POTENTIAL				
Scaling up	limited	low	low	good	v. good
Process control	medium	medium	low	v. good	v. good
	EFFECTIVITY				
Conversion efficiency	v. good	v. good	low	good	v. good
Thermal efficiency	v. good	v. good	good	good	v. good

Gasifiers Performance

Gasifier thermal power range



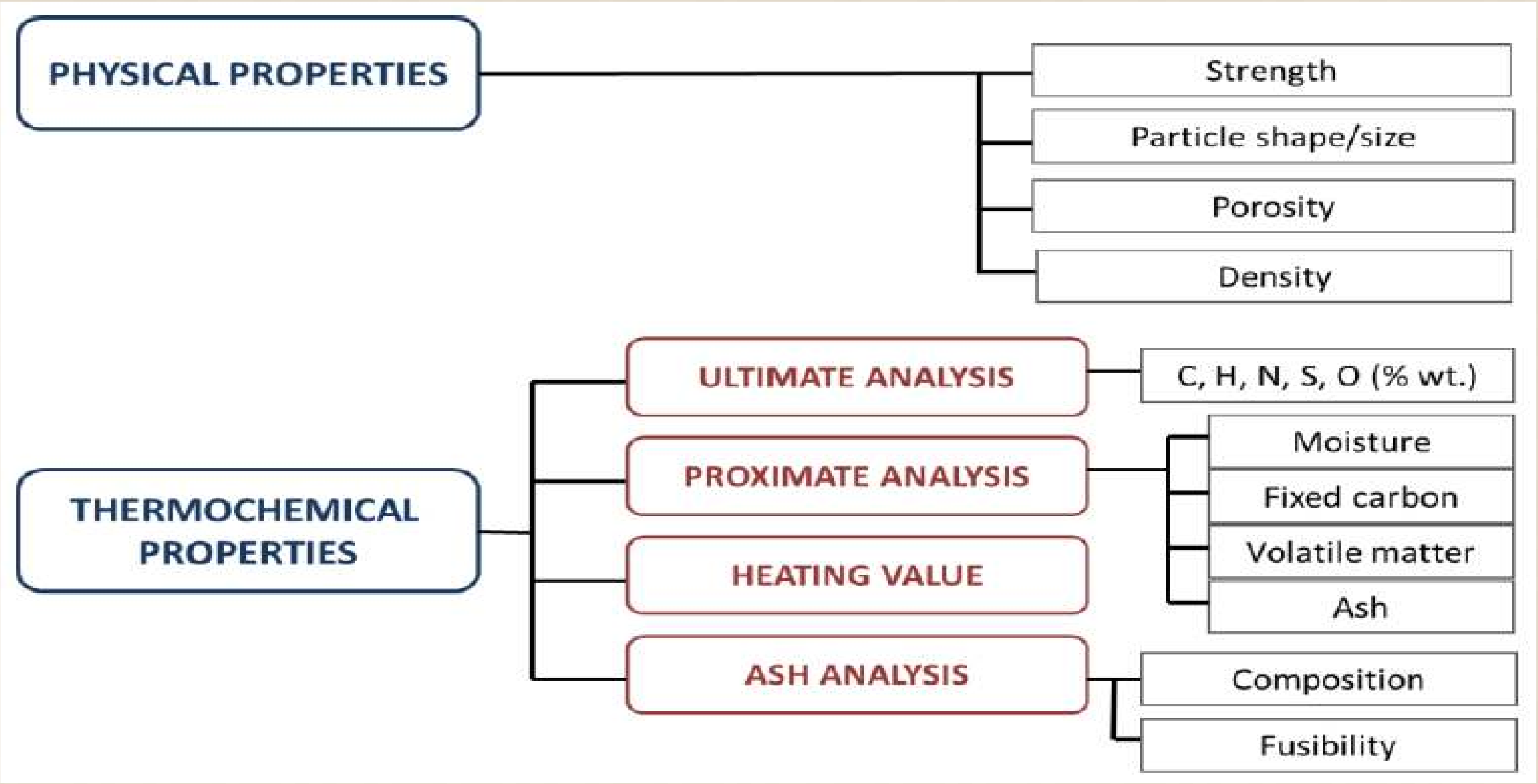
III- Design considerations

Introduction

- During the design of a gasification process, some basic calculation steps are of crucial importance.
- The calculations involves thermodynamic equilibrium and kinetics of reactions, mass & energy balance and process operating conditions.
- In all these steps, it is essential that composition, properties and temperature of the feed stream are known.
- The objective is to calculate, under specific conditions of temperature, pressure and flowrate, the producer gas composition and its energy content.
- As performance indicators, two frequent criteria are commonly evaluated, the gas thermal efficiency and the carbon conversion.

Basic data

Feedstocks properties



Basic data

Proximate, ultimate composition and heating values (HHV) of some biomass feedstocks

	Ultimate Analysis (wt% dry basis)						Proximate Analysis (wt% dry basis)			
	C	H	N	O	S	Ash	Moisture	Volatiles	Fixed Carbon	Heating Value HHV (MJ/kg)
Agricultural Residues										
Sawdust	50	6.3	0.8	43	0.03	0.03	7.8	74	25.5	19.3
Bagasse	48	6.0	-	42	-	4	1	80	15	17
Corn Cob	49	5.4	0.4	44.6	-	1	5.8	76.5	15	17
Short Rotation Woody Crops										
Beech Wood	50.4	7.2	0.3	41	0	1.0	19	85	14	18.4
Herbaceous Energy Crops										
Switchgrass	43	5.6	0.5	46	0.1	4.5	8.4	73	13.5	15.4
Straw	43.5	4.2	0.6	40.3	0.2	10.1	7.6	68.8	13.5	17
Miscanthus	49	4.6	0.4	46	0.1	1.9	7.9	79	11.5	12
Municipal Solid Waste										
Dry Sewage	20.5	3.2	2.3	17.5	0.6	56	4.7	41.6	2.3	8
Coals										
Subbituminous	67.8	4.7	0.9	17.2	0.6	8.7	31.0	43.6	47.7	24.6
Bituminous	61.5	4.2	1.2	6.0	5.1	21.9	8.7	36.1	42.0	27.0

Basic data

Equilibrium reactions and Kinetics

Combustion reactions

$C + ½\, O_2 = CO$	−111 MJ/kmol
$CO + ½\, O_2 = CO_2$	−283 MJ/kmol
$H_2 + ½\, O_2 = H_2O$	−242 MJ/kmol

Solid phase reduction reactions

$C + CO_2 \leftrightarrows 2\ CO$	+172 MJ/kmol	Boudouard reaction
$C + H_2O \leftrightarrows CO + H_2$	+131 MJ/kmol	Water gas reaction
$C + 2\ H_2 \leftrightarrows CH_4$	−75 MJ/kmol	Methanation

Gas phase reduction reactions

$CO + H_2O \leftrightarrows CO_2 + H_2$	−41 MJ/kmol	Water gas shift
$CH_4 + H_2O \leftrightarrows CO_2 + 3\ H_2$	+206 MJ/kmol	Steam methane reforming

$$Equilibrium\ constant, K_p(T) = \frac{k_r}{k_f} = \frac{Products\ concentrations}{Reactants\ concentrations}$$

$$k(T) = A.exp^{\frac{-E}{RT}}$$

Process equations

The basic equations needed for all gasification processes are

- Mass balance equations

1. Carbon balance.
2. Hydrogen balance.
3. Oxygen balance.

…

- Dalton equation, stating that the sum of the mole fractions in the product gas equals unity.

- Energy balance equations

$$(\text{heat of formation} + \text{sensible heat})_{\text{products}} + \text{indirect subtracted heat}$$
$$=$$
$$(\text{heat of formation} + \text{sensible heat})_{\text{feed}} + \text{indirect added heat}$$

- Reaction constants of the relevant reactions. In general, 3 for the heterogeneous case where carbon is present and 2 for the homogeneous case.

Performance parameters

Gasifier Efficiency

- **Performance of a gasifier is often expressed in terms of its efficiency, which can be defined in two different ways: <u>cold gas efficiency</u> and <u>hot gas efficiency</u>.**
- **The cold gas efficiency is used if the gas is used for running an internal combustion engine in which case it is cooled down to ambient temperature and tar vapors are removed from the gas.**
- **For thermal applications, the gas is not cooled before combustion and the sensible heat of the gas is also useful**

$$\eta_{ceff} = (V_g C_g)/(M_b C_b)$$

V_g = gas flue generation rate (m^3/s)

C_g = heating value of the gas (kJ/m^3)

M_b = biomass consumption rate (kg/s)

C_b = calorific value of biomass (kJ/m^3)

Typical value: 70 %

$$\eta_{heff} = (V_g C_g + H_{sensible})/(M_b C_b)$$

$H_{sensible} = C_p V_g (t_g - t_a)$

t_g = gas temperature

t_a = ambient temperature

Typical value: 75 %

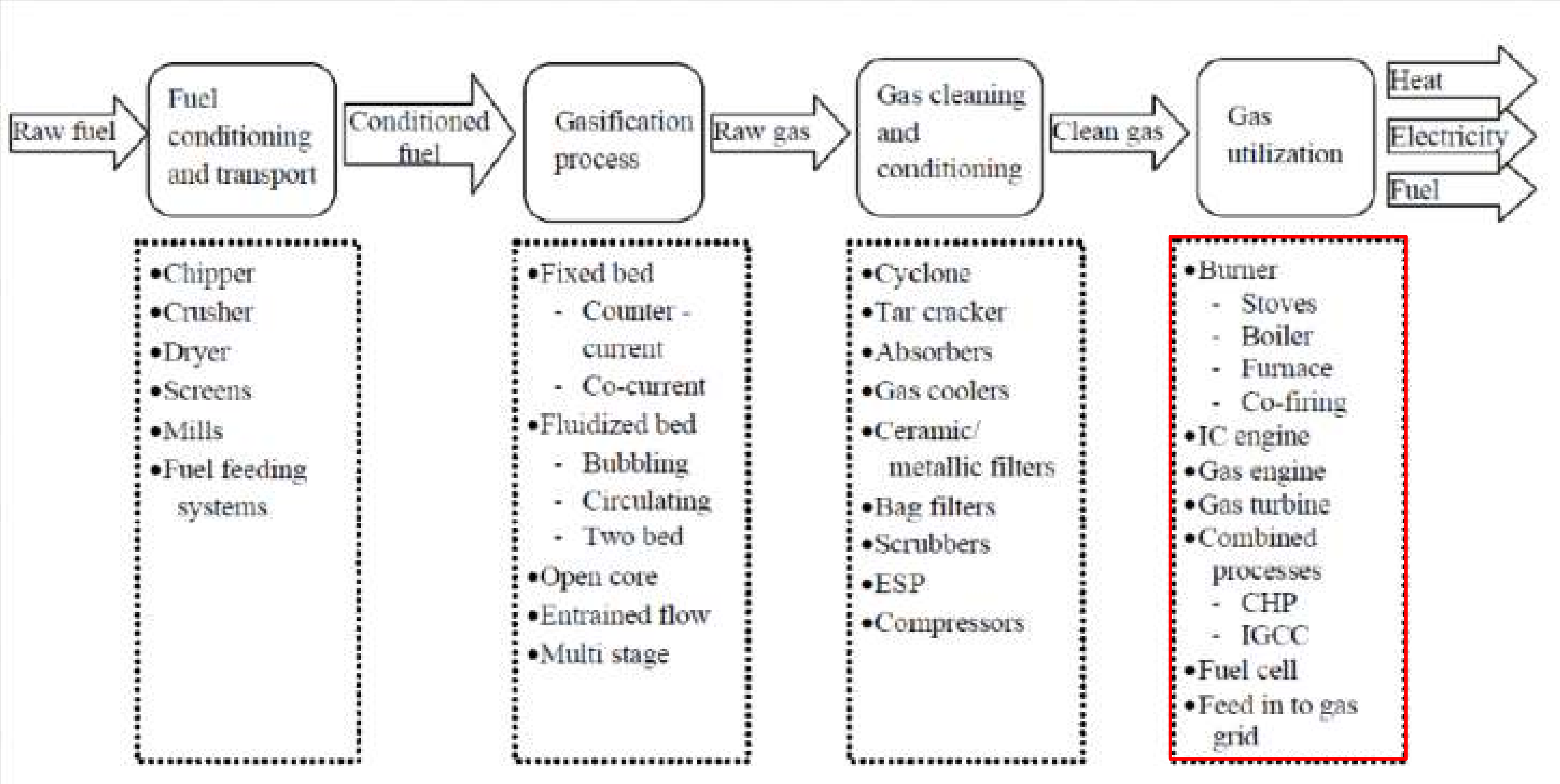
Carbon Conversion

$$Carbon\ conversion\ [\%] = \left\{1 - \frac{Carbon\ in\ gasification\ residue\ [kmol/h]}{Carbon\ in\ feedstock\ [kmol/h]}\right\} \times 100$$

IV- Applications related to gasification

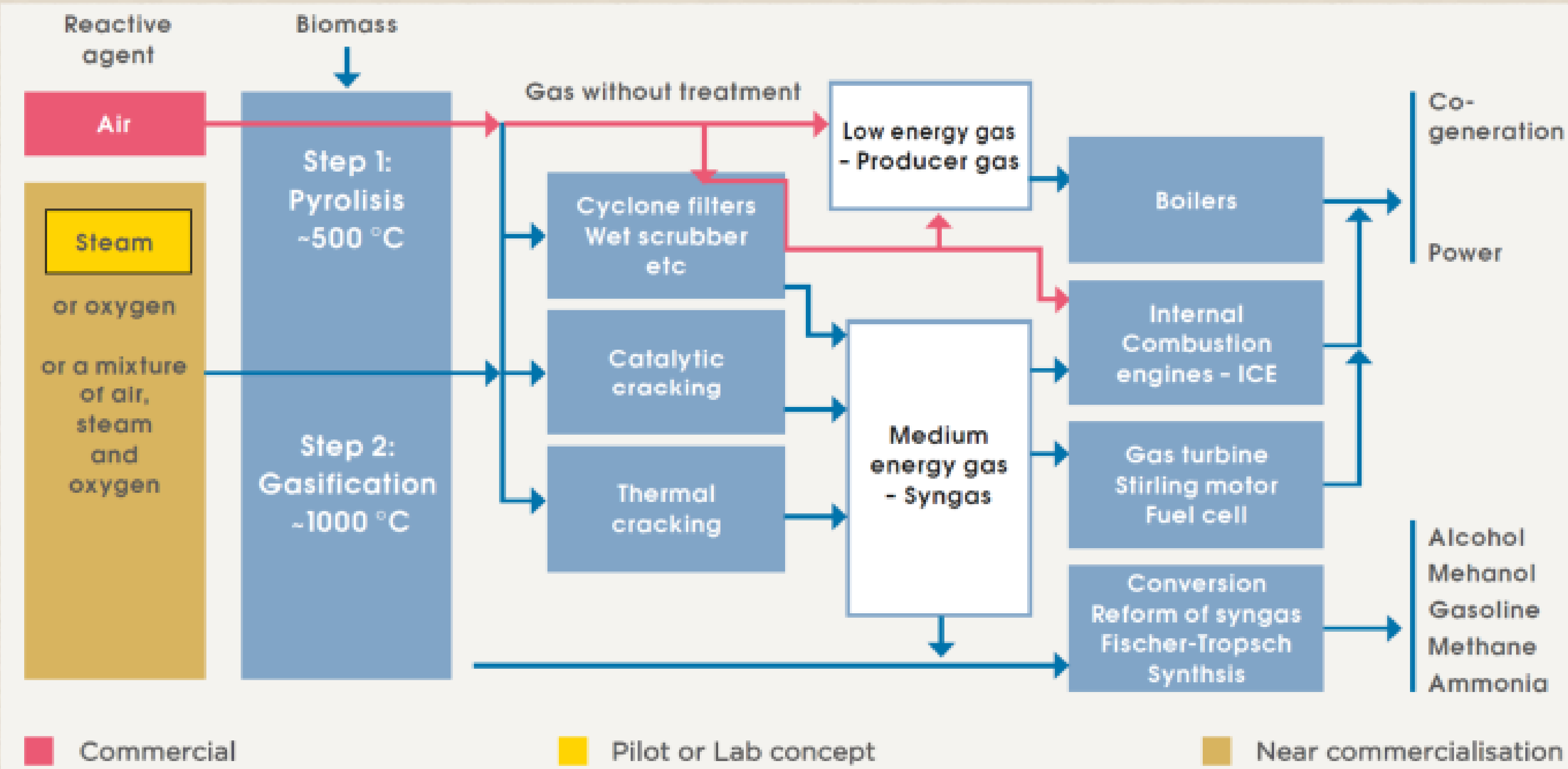
IV- Applications related to gasification

Process steps of a biomass gasification plant



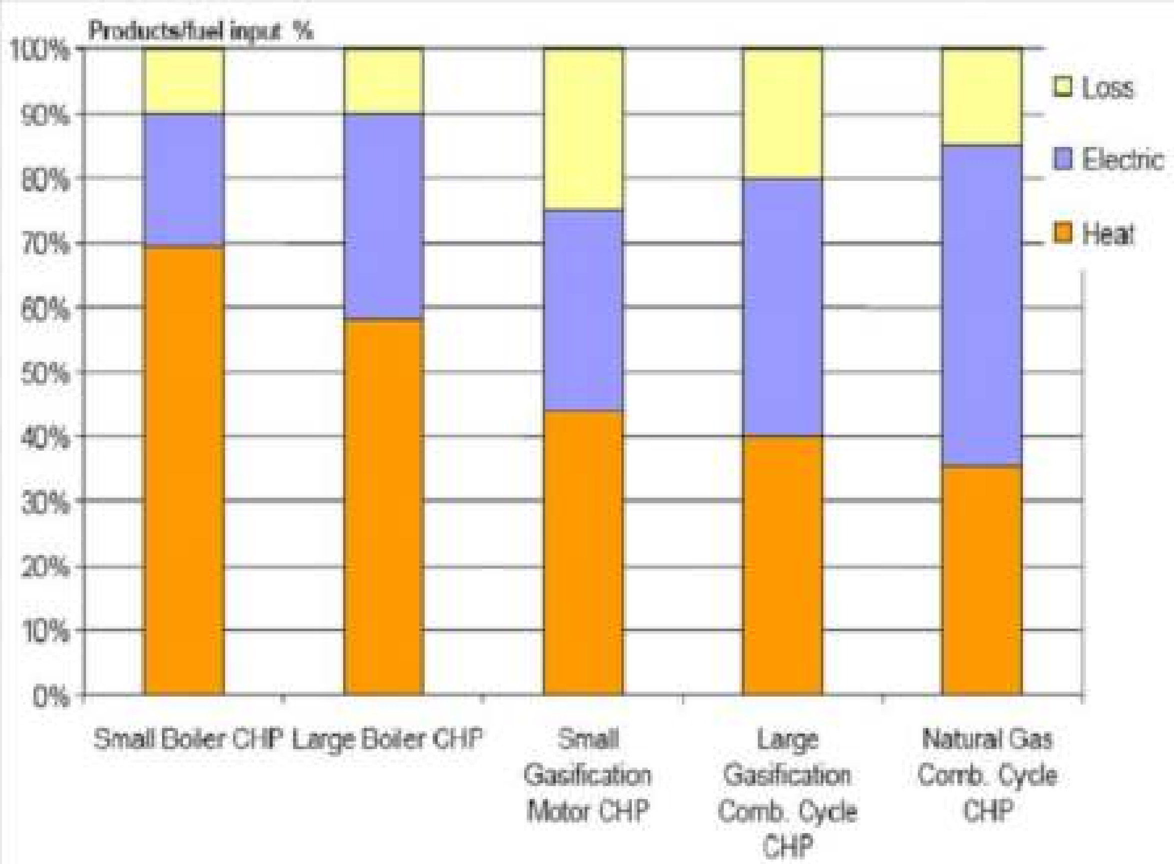
IV- Applications related to gasification

Gasification end-use



Source: SADAKA 2010

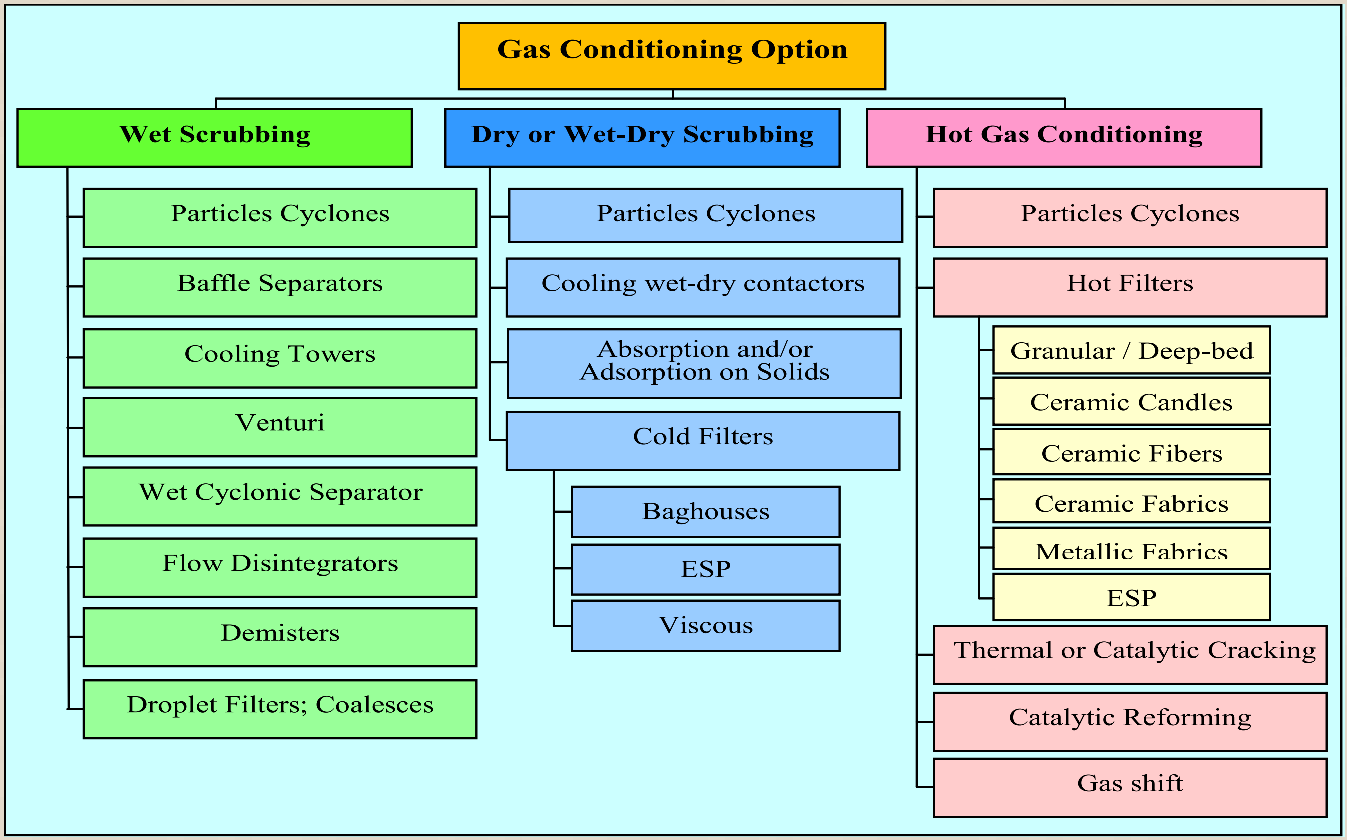
Efficiency vs. syngas utilization



Source: TPS Termiska Processer AB

Gas cleaning and conditioning methods

- Several chemical and physical methods for contaminants removal are available
- The main contaminants to be removed are: **water, sulfur compounds, tars** and **particulates**

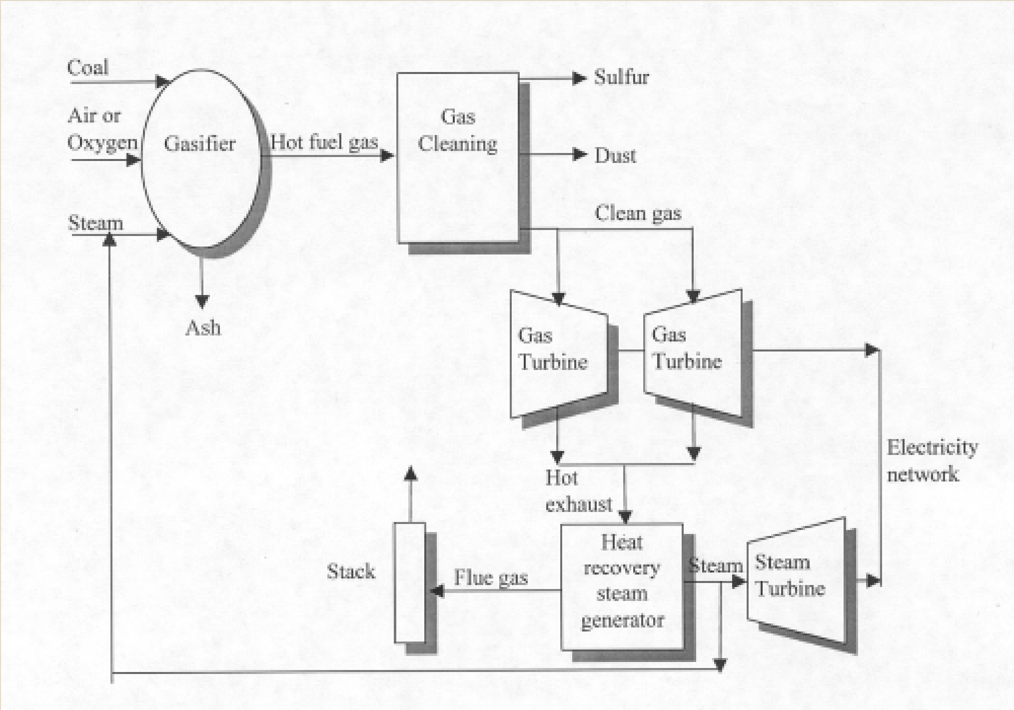


IV- Applications related to gasification

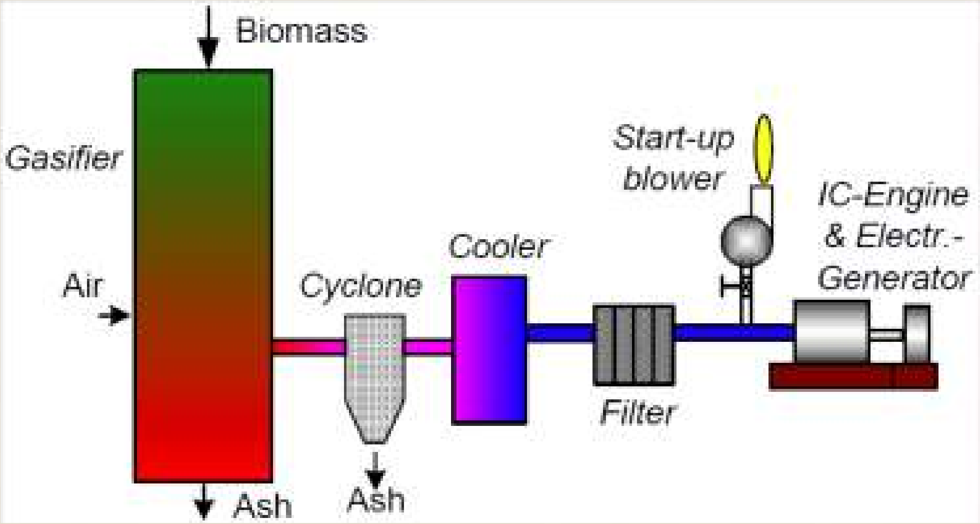
Producer gas applications and quality requirement

Product	**Synthetic Fuels**	**Methanol**	**Hydrogen**	**Fuel Gas**	
	FT Gasoline & Diesel			Boiler	Turbine
H_2/CO	0.6 [a]	~2.0	High	Unimportant	Unimportant
CO_2	Low	Low [c]	Not Important [b]	Not Critical	Not Critical
Hydrocarbons	Low [d]	Low [d]	Low [d]	High	High
N_2	Low	Low	Low	Note [e]	Note [e]
H_2O	Low	Low	High [f]	Low	Note [g]
Contaminants	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	Note [k]	Low Part. Low Metals
Heating Value	Unimportant [h]	Unimportant [h]	Unimportant [h]	High [i]	High [i]
Pressure, bar	~20-30	~50 (liquid phase) ~140 (vapor phase)	~28	Low	~400
Temperature, ^oC	200-300 [j] 300-400	100-200	100-200	250	500-600

Practical gasification systems



Typical IGCC system (100 MW)



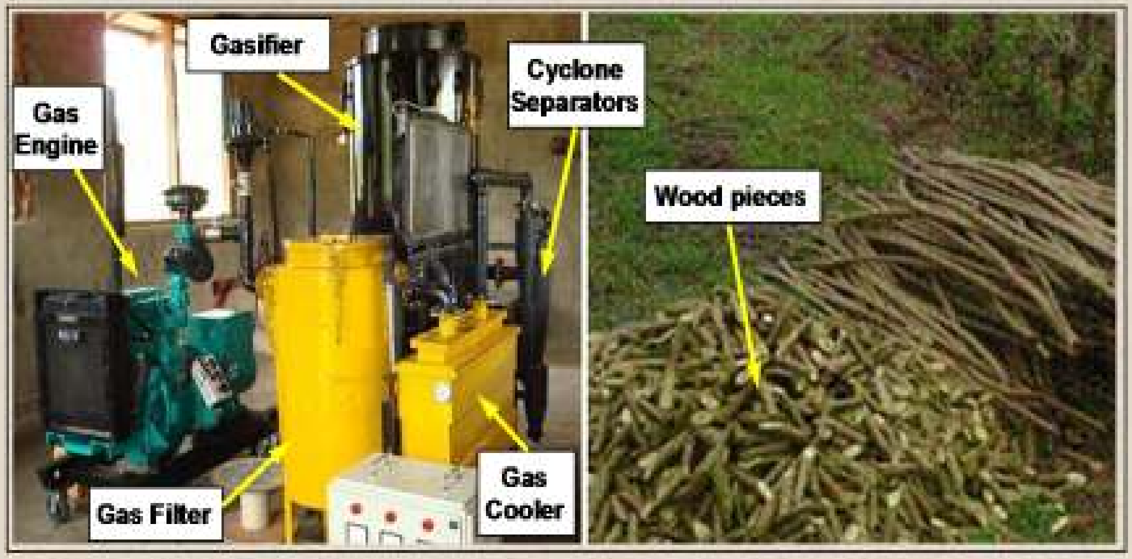
Typical small-scale gasifier-engine power plant (5 – 100 kW)

IV- Applications related to gasification

Practical gasification systems

The two-burner rice husk gas stove - Philippines

Institutional Cookstove



3.5 kWe fuel wood gasifier - IC engine system in Sri Lanka

Small scale electricity generation

Industrial gasifier (2 MWth)

Thank you