King Saud University

Sustainable Energy Technologies Center (SET)

BIOMASS GROUP

# Introduction to Biomass Energy Conversions

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

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

# Outline

- **Introduction**

1. Energy Context
2. Biomass as Renewable Energy Resources

- **Bioenergy production overview**

1. Biomass to energy routes
2. Energy conversion systems

- **Conversion Technologies**

1. Thermochemical Processes
2. Biochemical Processes

# Introduction
# Energy context

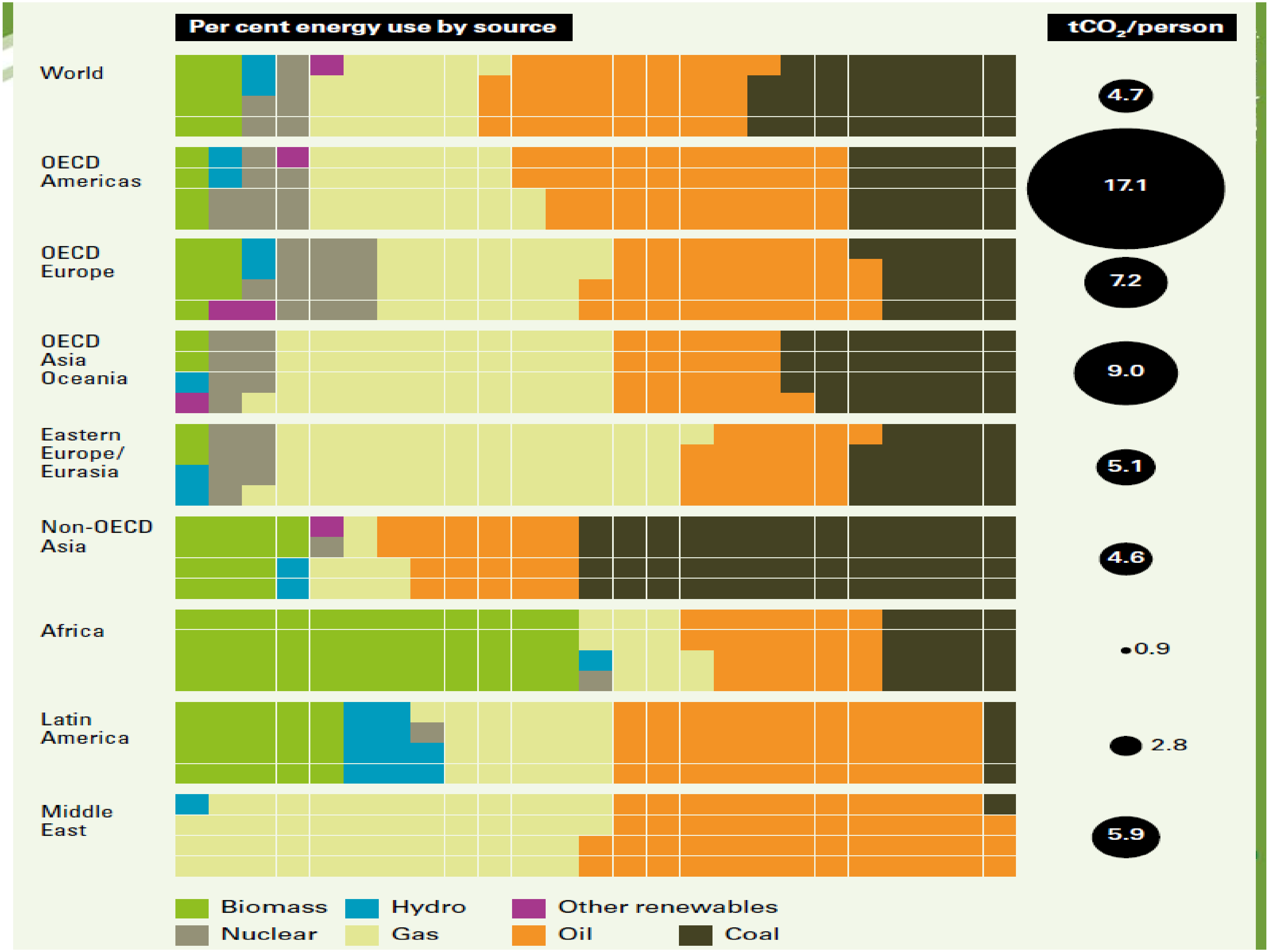
- World population is rising (8.3 billion by 2030)

Global energy use increase

- GHG emissions to the atmosphere (especially $CO_2$)

- Renewable energy offer a good mechanism to reduce carbon emissions.

Meet the requirements (Sustainability)



Per cent energy use by source
tCO2/person
World
OECD Americas
OECD Europe
OECD Asia Oceania
Eastern Europe/ Eurasia
Non-OECD Asia
Africa
Latin America
Middle East
4.7
17.1
7.2
9.0
5.1
4.6
0.9
2.8
5.9
Biomass
Hydro
Other renewables
Nuclear
Gas
Oil
Coal

# Introduction

## Biomass as a renewable resource

- Biomass is biological organic matter derived from living or recently-living organisms
- Bioenergy is the energy contained (stored) in 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)

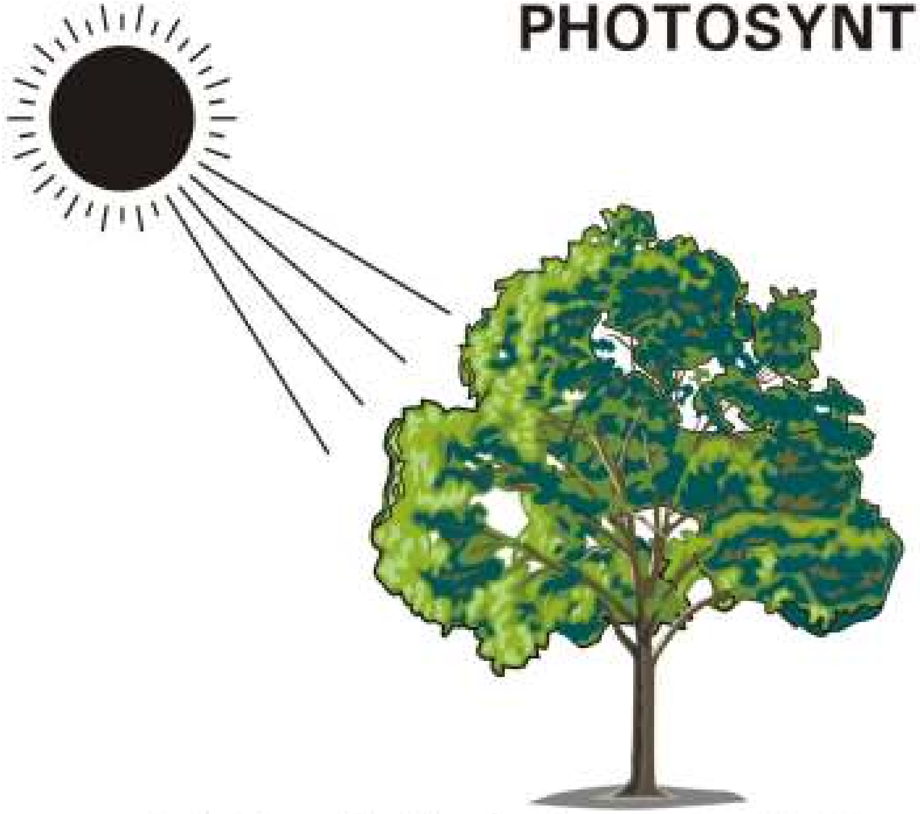
Secondary: materials that undergone significant changes from raw biomass. Paper, cardboard, cotton, natural rubber products, and used cooking oils.

# Introduction

## Biomass as a renewable resource

# How Biomass gets its energy

## PHOTOSYNTHESIS



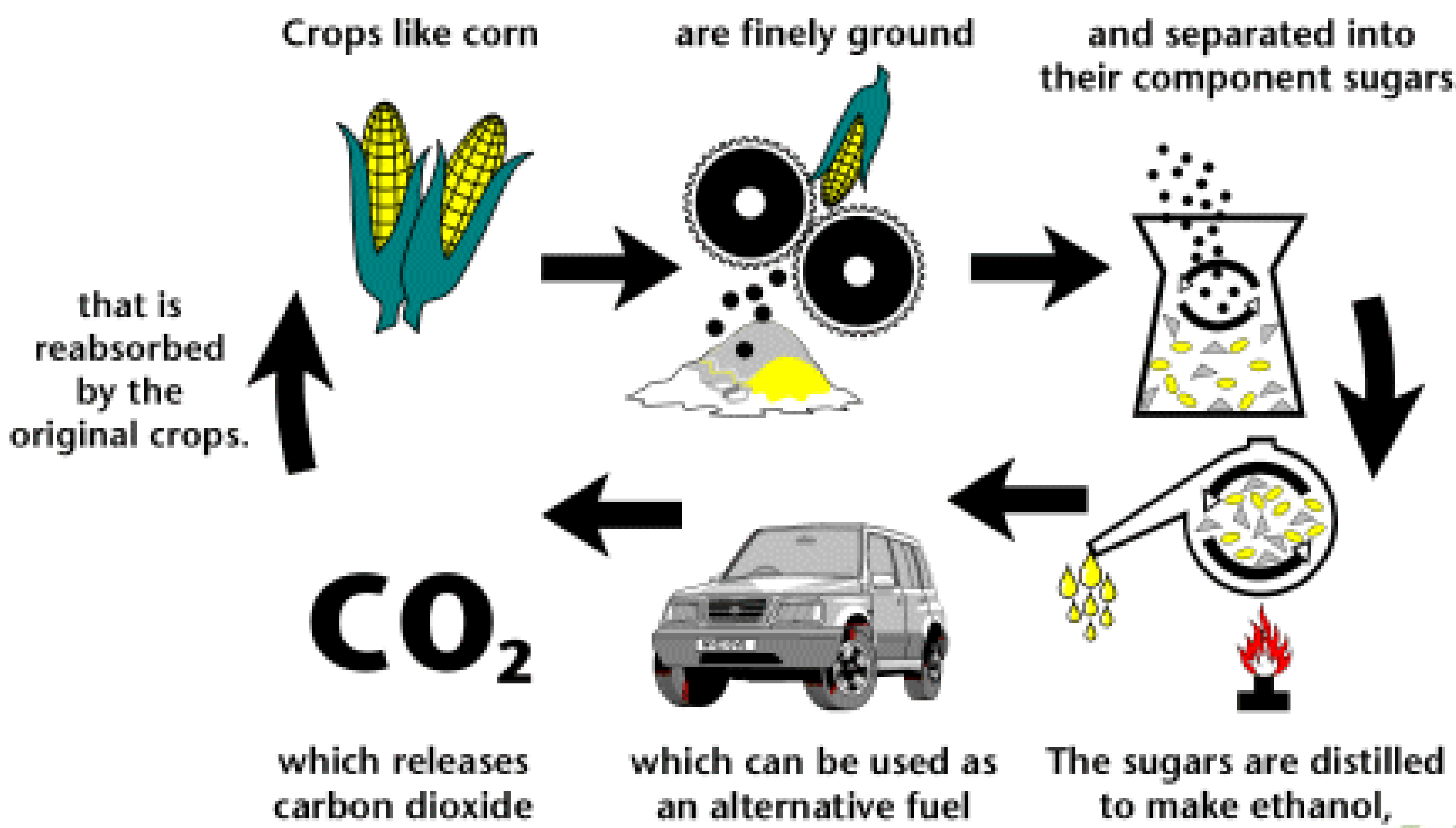
In the process of photosynthesis, plants convert radiant energy from the sun into chemical energy in the form of glucose - or sugar.

water + carbon dioxide + sunlight $\longrightarrow$ glucose + oxygen

$$6\,H_2O + 6\,CO_2 + \text{radiant energy} \longrightarrow C_6H_{12}O_6 + 6\,O_2$$

# The carbon cycle

## Example of Bioethanol Production

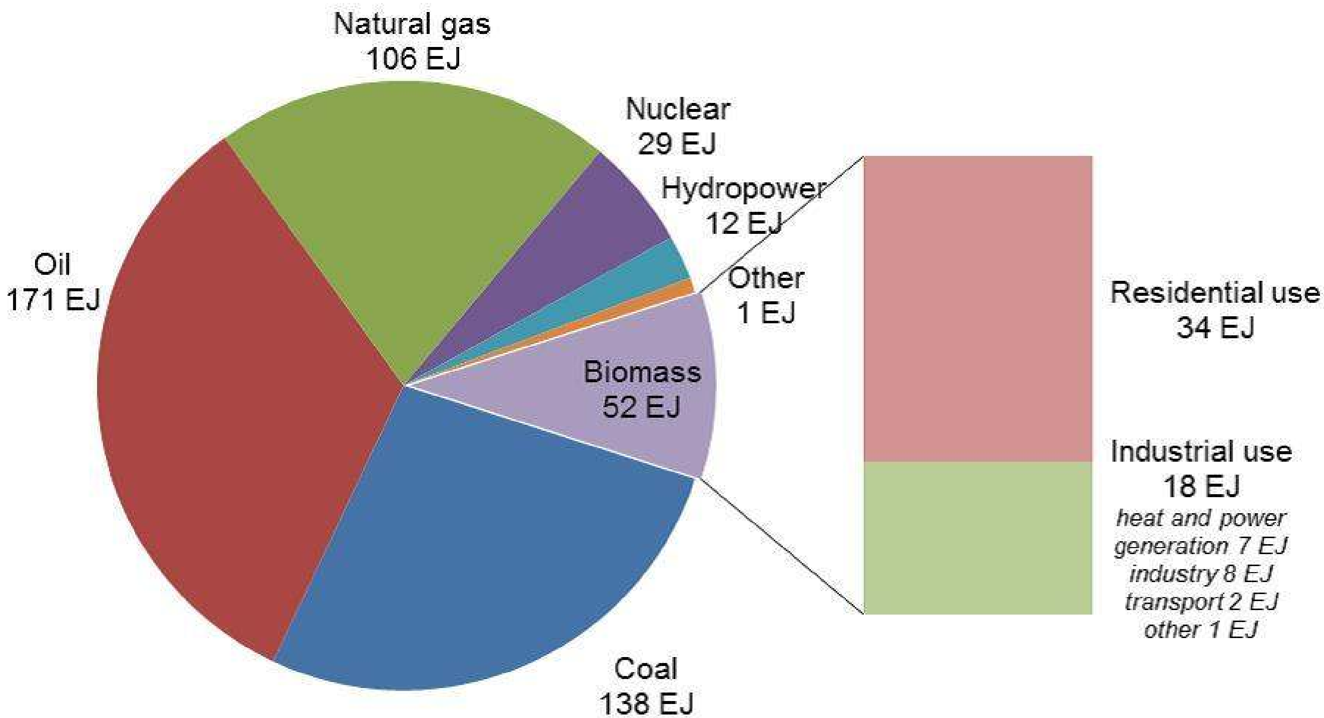


# Bioenergy Production Overview

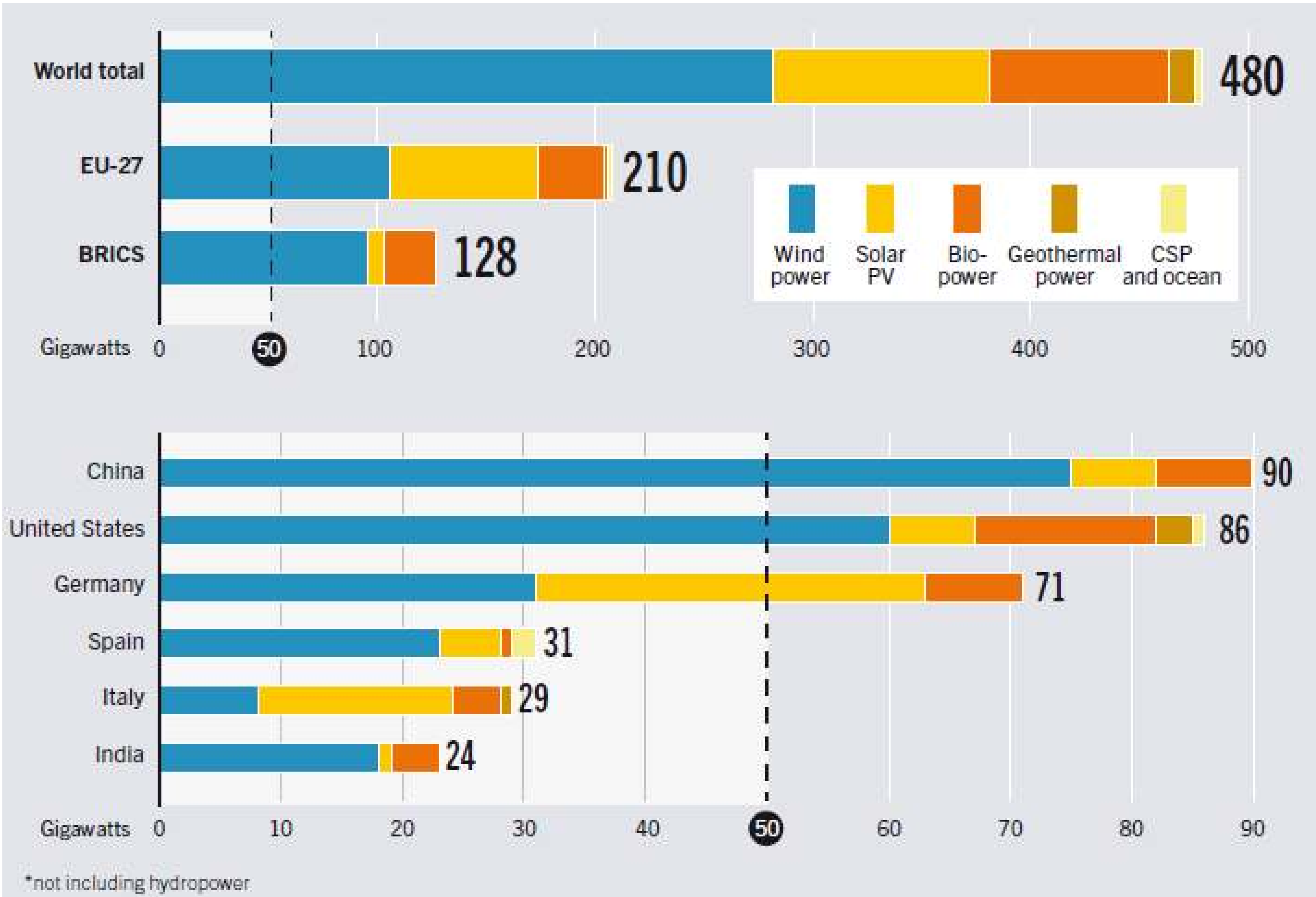
# Bioenergy

- Bioenergy is the energy retrieved from biomass sources. It is the largest used renewable energy resource in the world
- Large bioenergy potential: Biomass resource is widely available and diversified in the Kingdom: Livestock waste, Municipal and Industrial effluents (paper, plastic, food, …etc.), Poultry waste, Sewage sludge
- Bioenergy is a significant mean for waste disposal to prevent environmental pollution and allow economic stability
- Main Technologies:
  - Biogas based power plant technology
  - Gasification power plant technology
  - Biodiesel and Bioethanol Plants technology

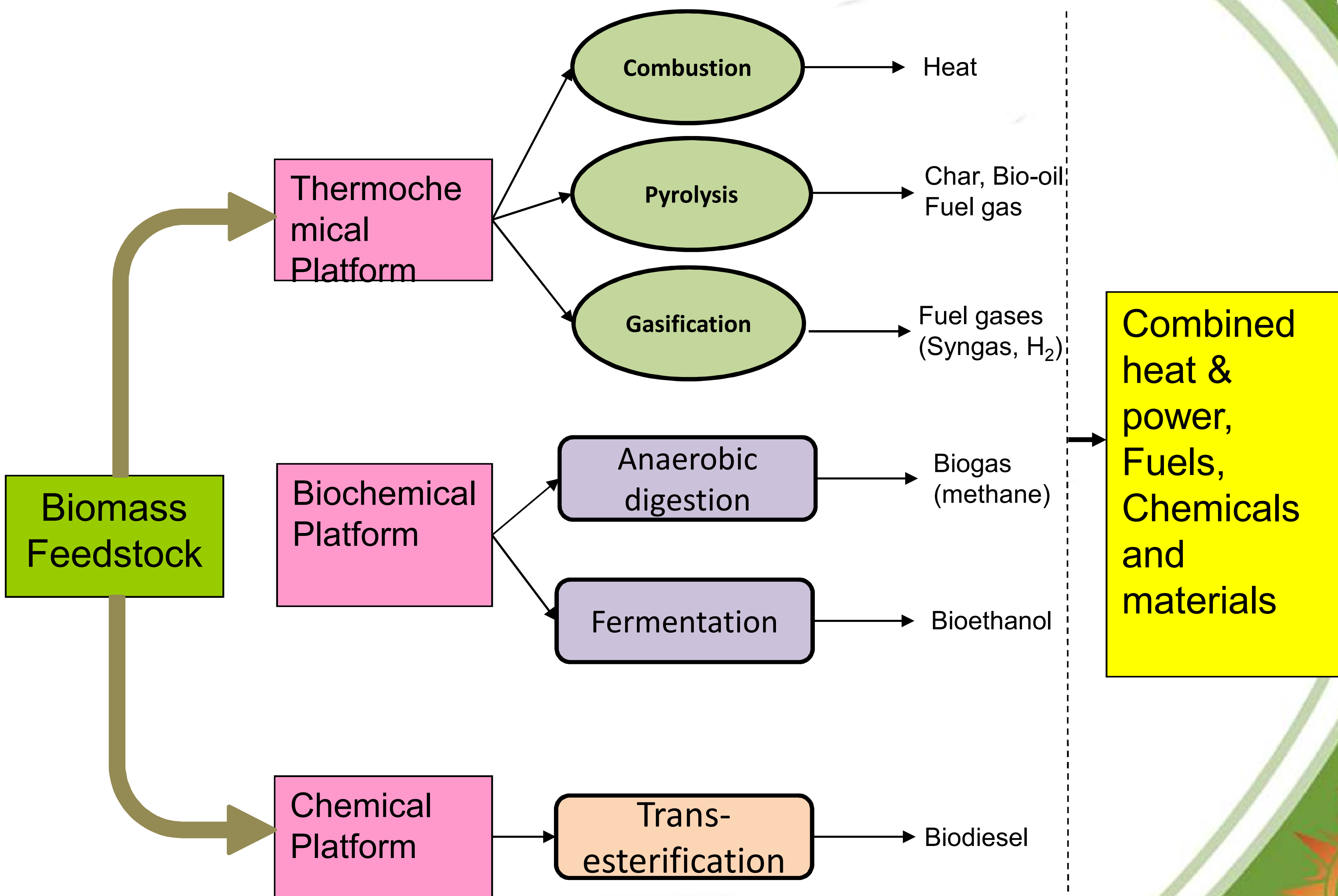
## Biomass provides more than 10 % of Global energy use (International Energy Agency, 2013)



# Renewable Power Capacities in World
## (International Energy Agency, 2012*)



# Bioenergy Production Routes



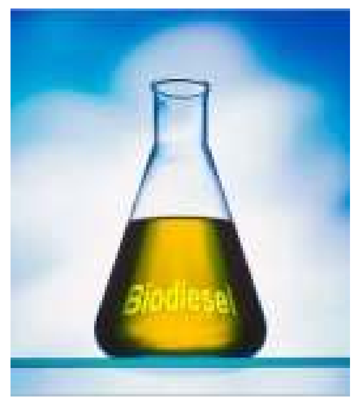
# Pyrolysis products

Bio-oil

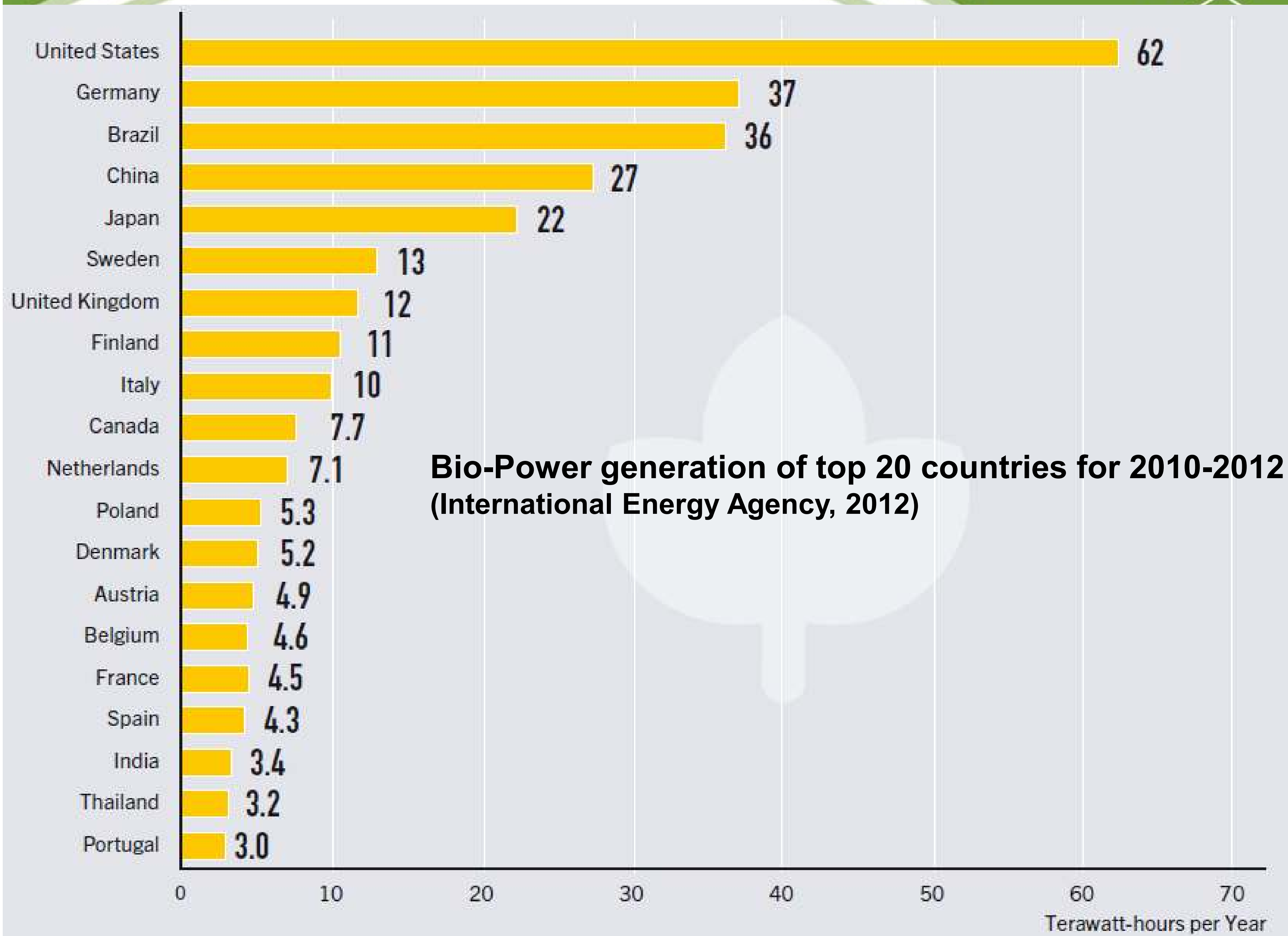
Char

Syngas

Bioethanol



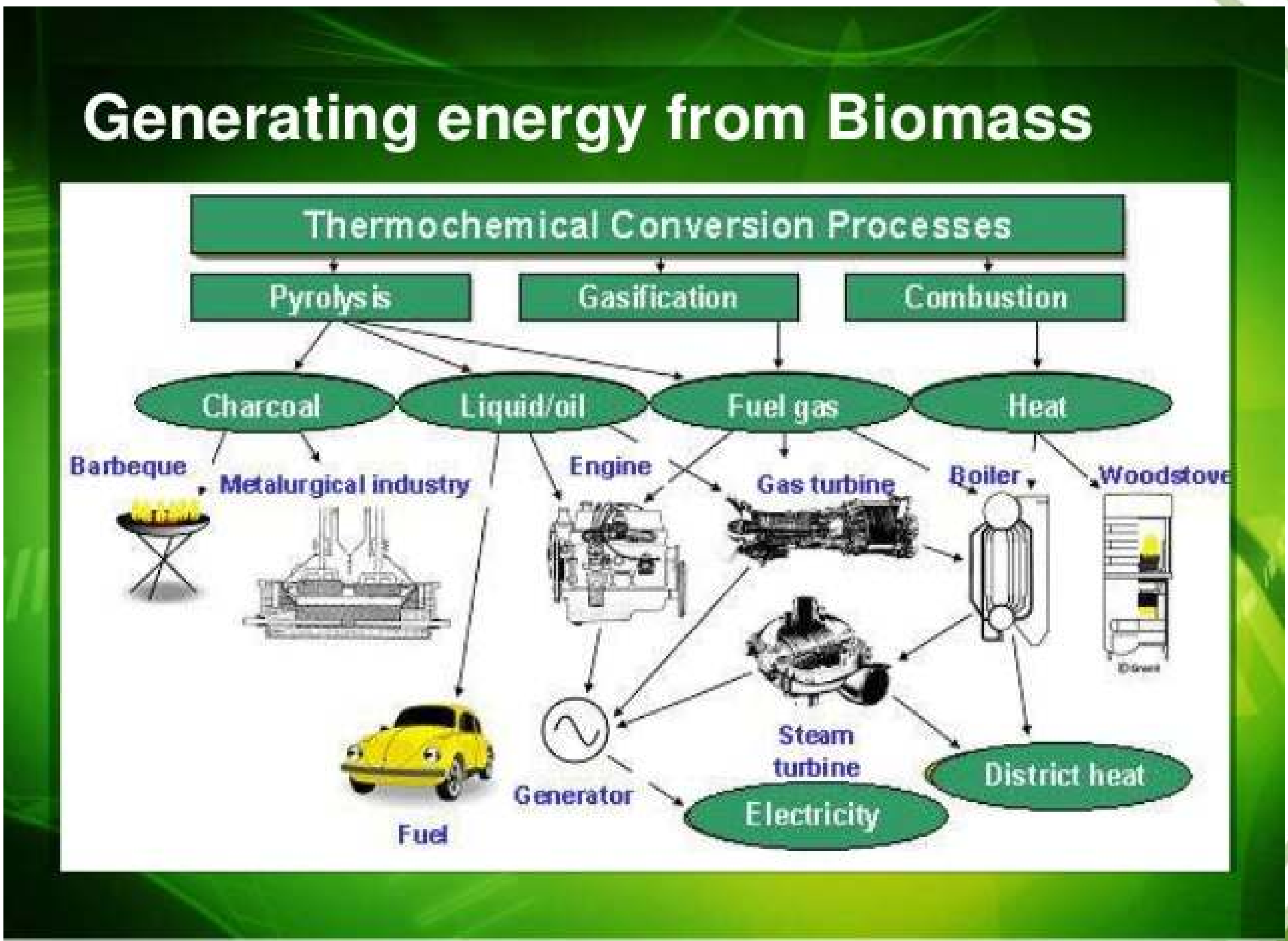

Biodiesel



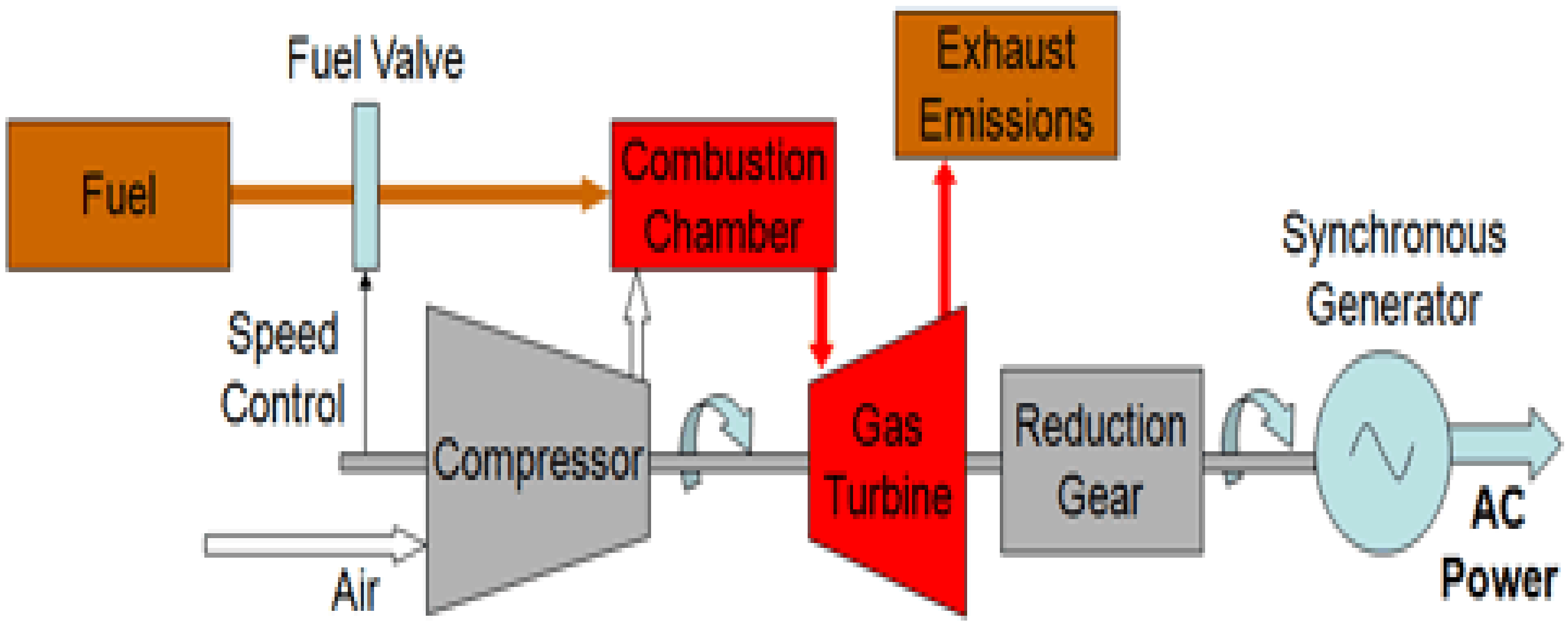

**Bio-Power generation of top 20 countries for 2010-2012**
**(International Energy Agency, 2012)**

## Global Production of Bioethanol and Biodiesel
**(International Energy Agency, 2012)**

# Energy generation systems



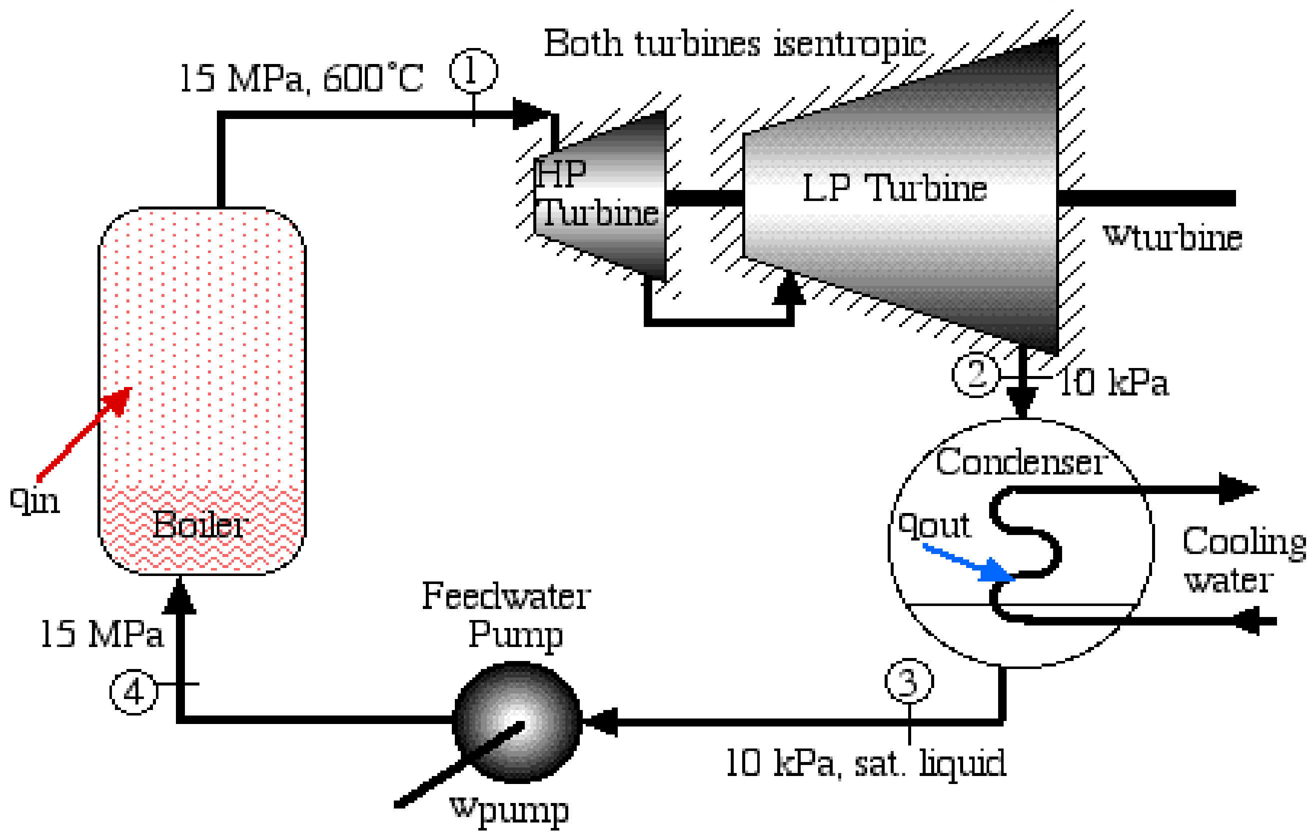
# Energy generation systems




Gas Turbine Electric Power Generation

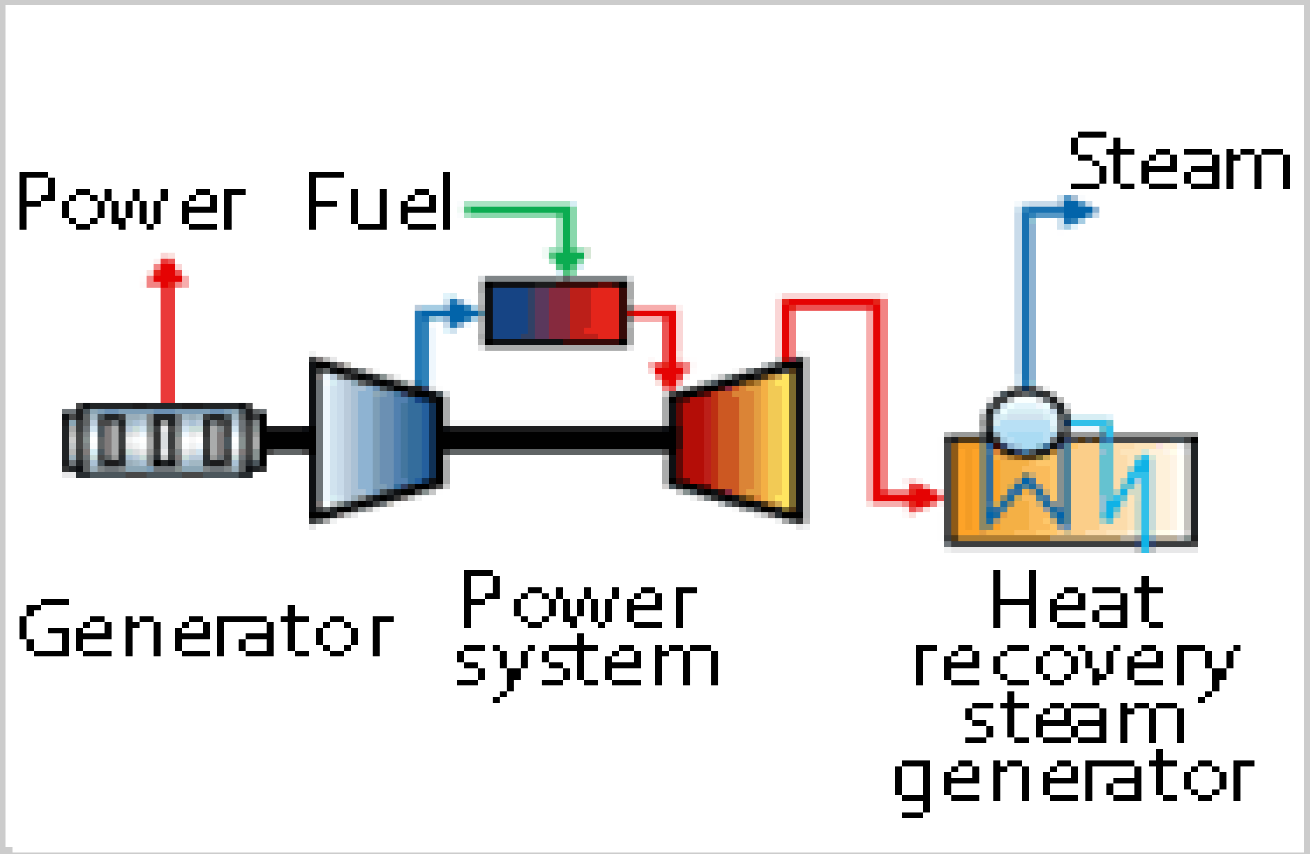
# Energy generation systems

**Steam turbine**



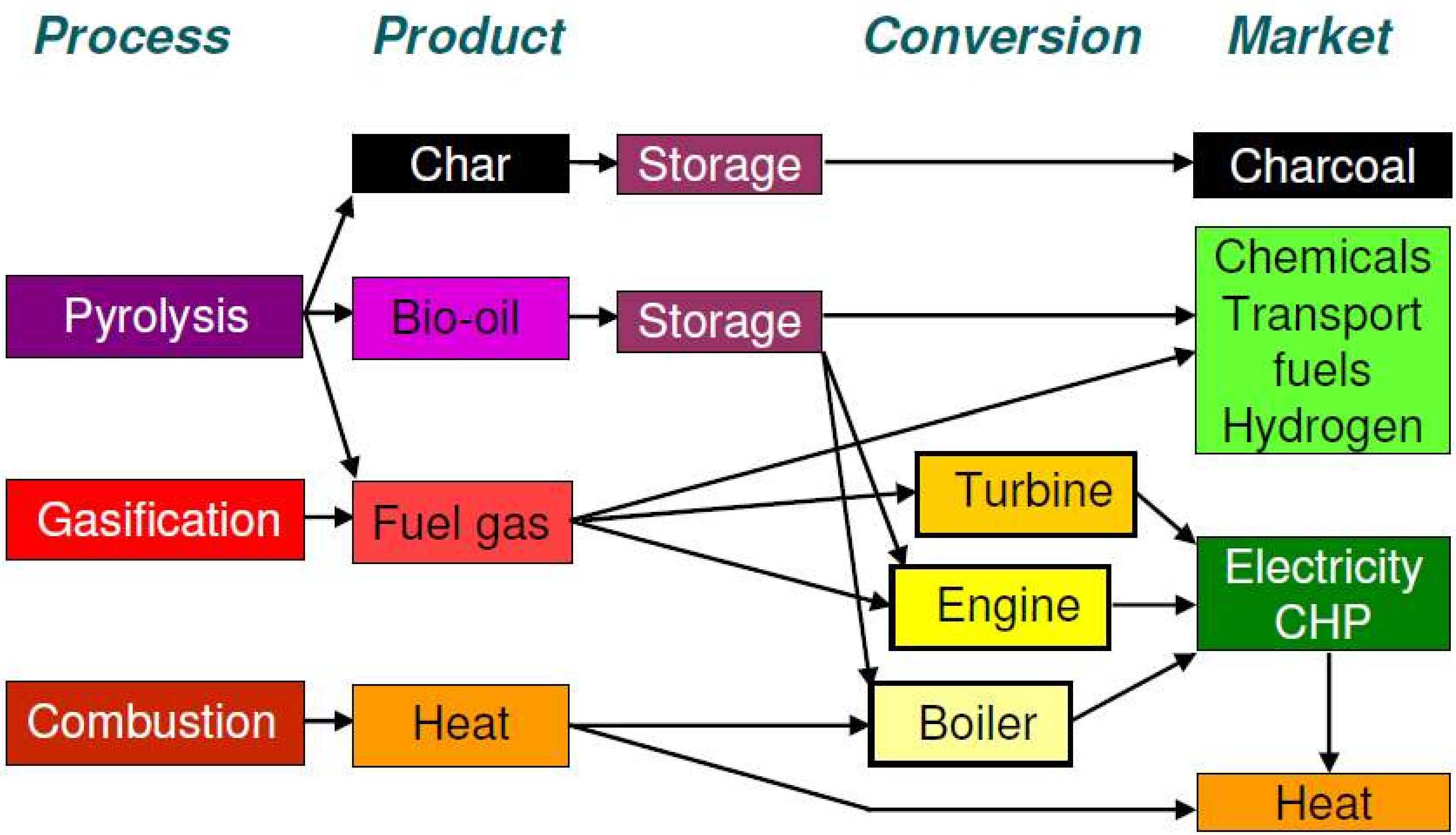
# Energy generation systems

**Combined heat & power system**

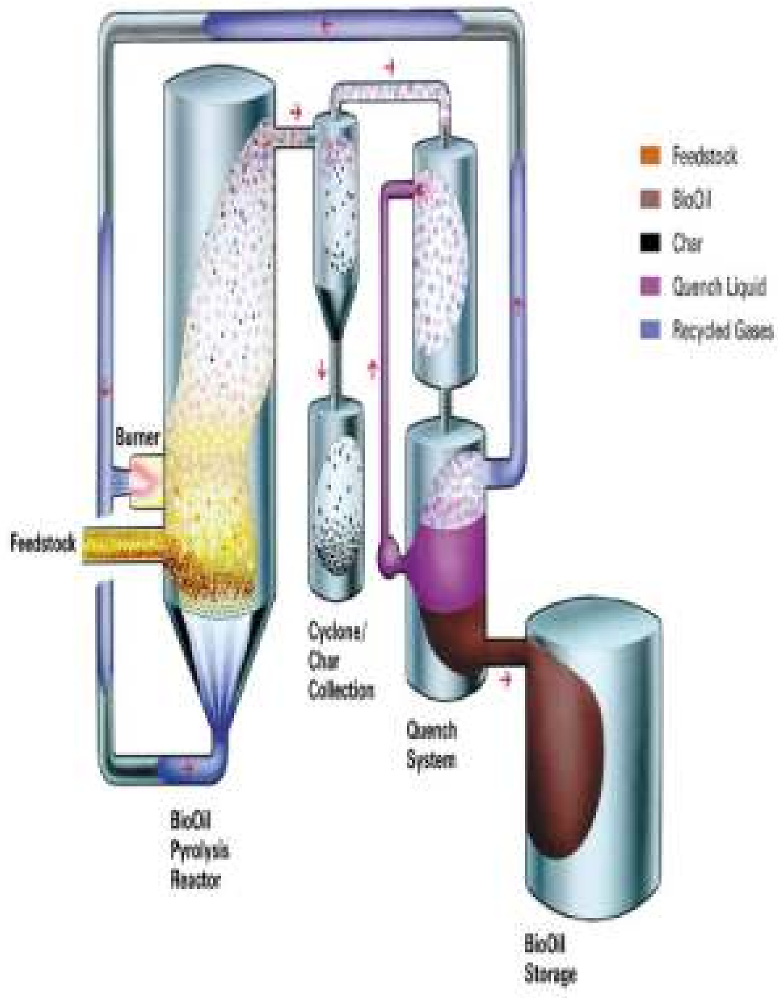


# Biomass Energy Conversions Technologies
# 1- Thermochemical processes

# Thermochemical conversion options



# Pyrolysis




- Thermal decomposition of solid biomass by heat in absence of oxygen
- First step of in combustion and gasification processes
- Biomass is converted into solid charcoal, liquid (bio-oil) and gas
- The process is endothermic
- Because some oxygen is unavoidable in any pyrolysis system, a small amount of oxidation occurs

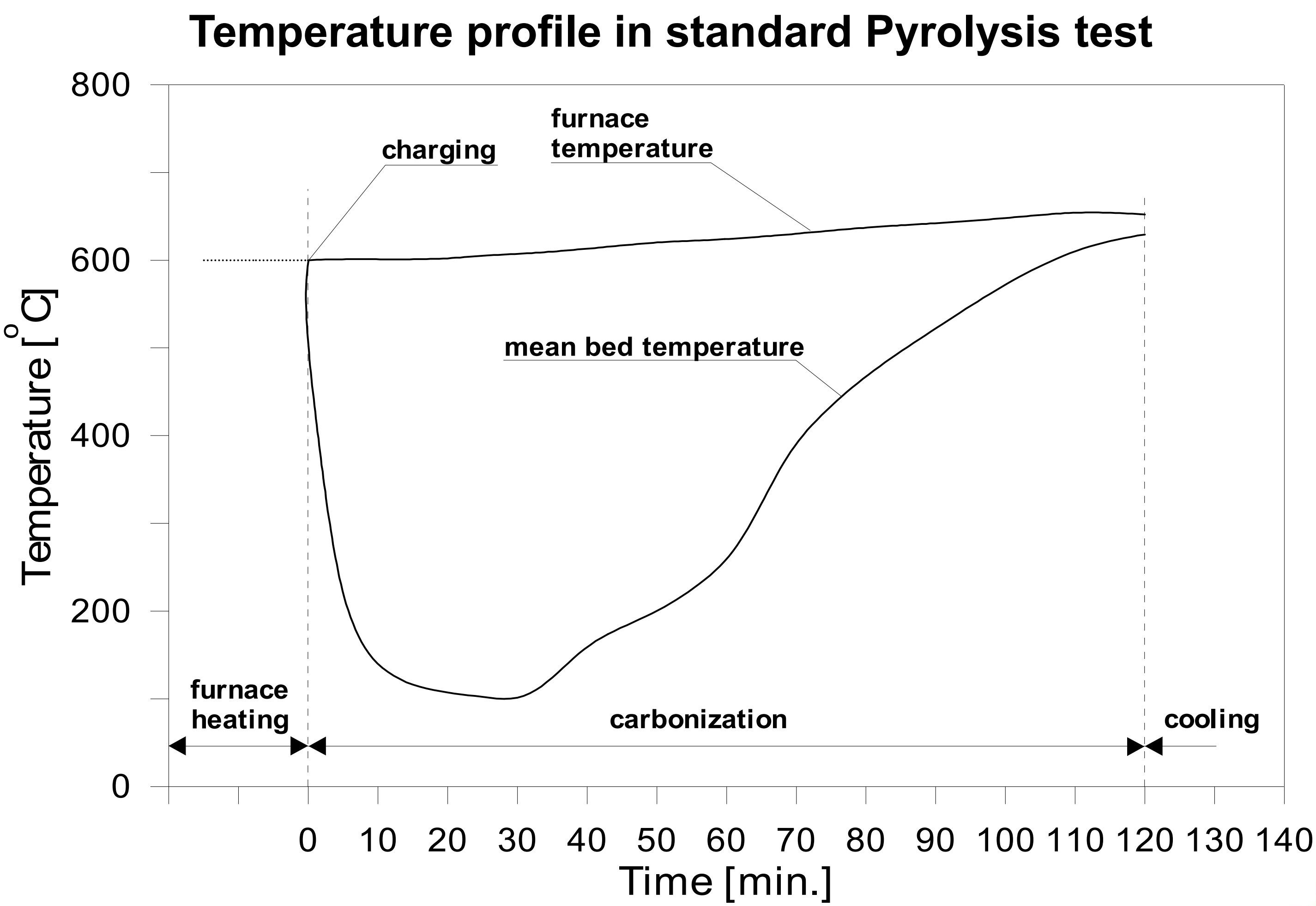
**Dry Biomass → char + (CO, $CO_2$, $H_2$, $H_2O$ (g), $CH_4$) + tars + Ash**

# Pyrolysis

## Classification of Pyrolysis methods

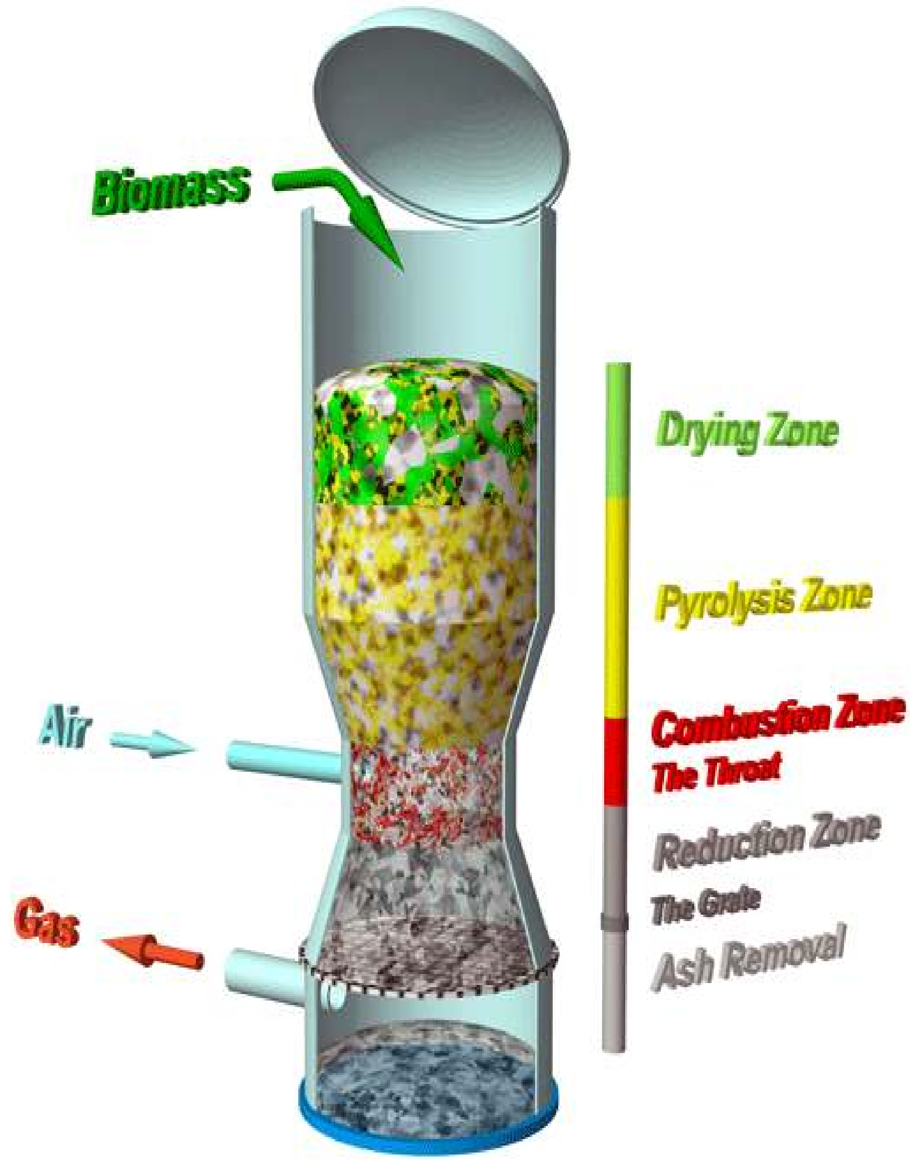
| Mode | Conditions | Liquid | Solid | Gas |
|---|---|---|---|---|
| Fast | Reactor temperature 500°C, very high heating rates > 1000°C/sec, short hot vapour residence ~1 s | 75% | 12% char | 13% |
| Intermediate | Reactor temperature 400-500°C, heating rate range 1 – 1000°C/sec, hot vapour residence ~10-30 s | 50% | 25% char | 25% |
| Slow – Torrefaction | Reactor temperature ~290°C, heating rate up to 1°C/sec, solids residence time ~30 min | 0-5% | 77% solid | 23% |
| Slow – Carbonisation | Reactor temperature 400-500°C, heating rate up to 1°C/sec, long solid residence hrs – days | 30% | 33% char | 35% |

# Typical Pyrolysis results



# Gasification

- Conversion of solid biomass into combustible gas mixture called producer gas ($CO + H_2 + CH_4$) in presence of limited ($O_2$/air)
- Involves partial combustion of biomass (controlled combustion)
- Four distinct process in the gasifier




**Basic Process Chemistry schematic**

# Gasification

## Producer Gas Characteristics

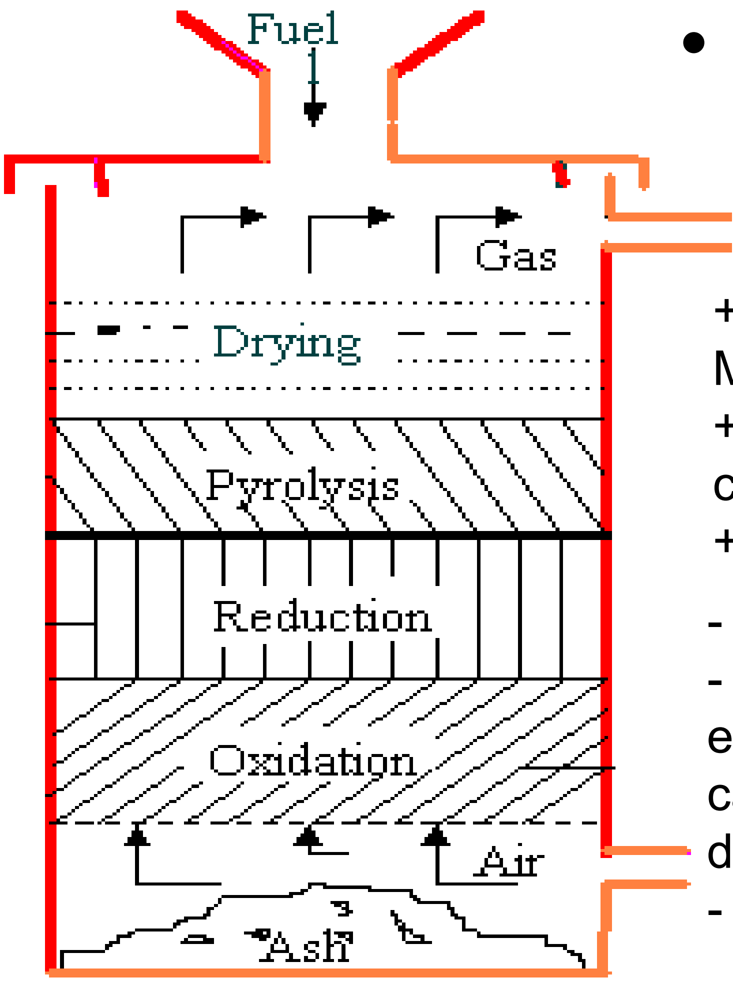
| Component | Rice Husk | Woody Biomass |
|---|---|---|
| CO | 15-20% | 15-20% |
| $H_2$ | 10-15% | 15-20% |
| $CH_4$ | Upto 4% | Upto 3% |
| $N_2$ | 45-55% | 45-50% |
| $CO_2$ | 8-12% | 8-12% |
| Gas C.V. (kcal/$Nm^3$) | Above 1050 | Above 1100 |
| Gas generated in $Nm^3$/kg of biomass | 2 | 2.5 |

# Gasification

## Classification of Gasification methods

| Classification | Conditional factor |
| --- | --- |
| Gasification pressure | Normal pressure (0.1-0.12 MPa), High pressure (0.5-2.5 MPa) |
| Gasification temperature | Low (< 700 °C), High (> 700 °), High temperature decomposition (> ash fusion point) |
| Gasification agent | Air, oxygen, steam and combination of them, carbon dioxide for particular time |
| Heating (temperature zone formation) | Direct (heat generation from reaction of partial gasification raw material and oxygen)<br>Indirect (external heat) |
| Gasifier types | Fixed bed, flow-bed, circulating flow bed, entrained bed, mixing bed, rotary kiln, twin tower, molten furnace |

## Gasifier types

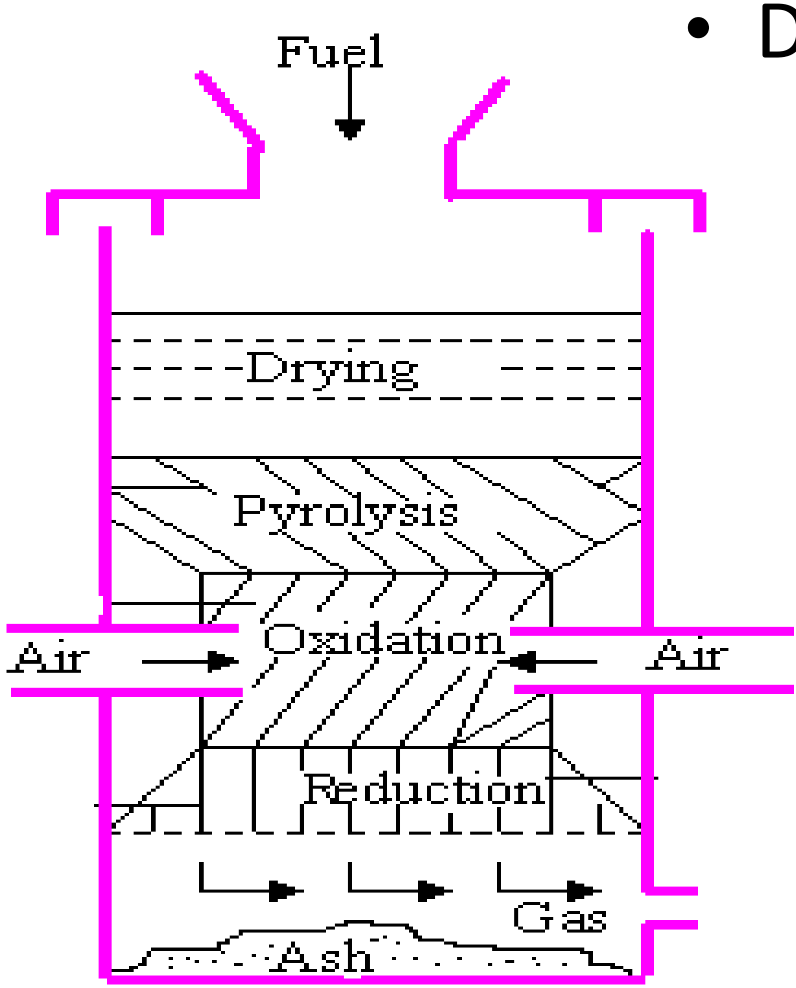



- Updraft Gasifier

+ Suitable for moderate outputs [2-12 MWe]
+ Good fuel flexibility [fines, small & large chips]
+ Good turndown

- Low gas quality
- Very high tars [100g/nm3] – requires extensive secondary tar cracking with catalysts [Ni based or dolomite]
- High capital cost

## Gasifier types

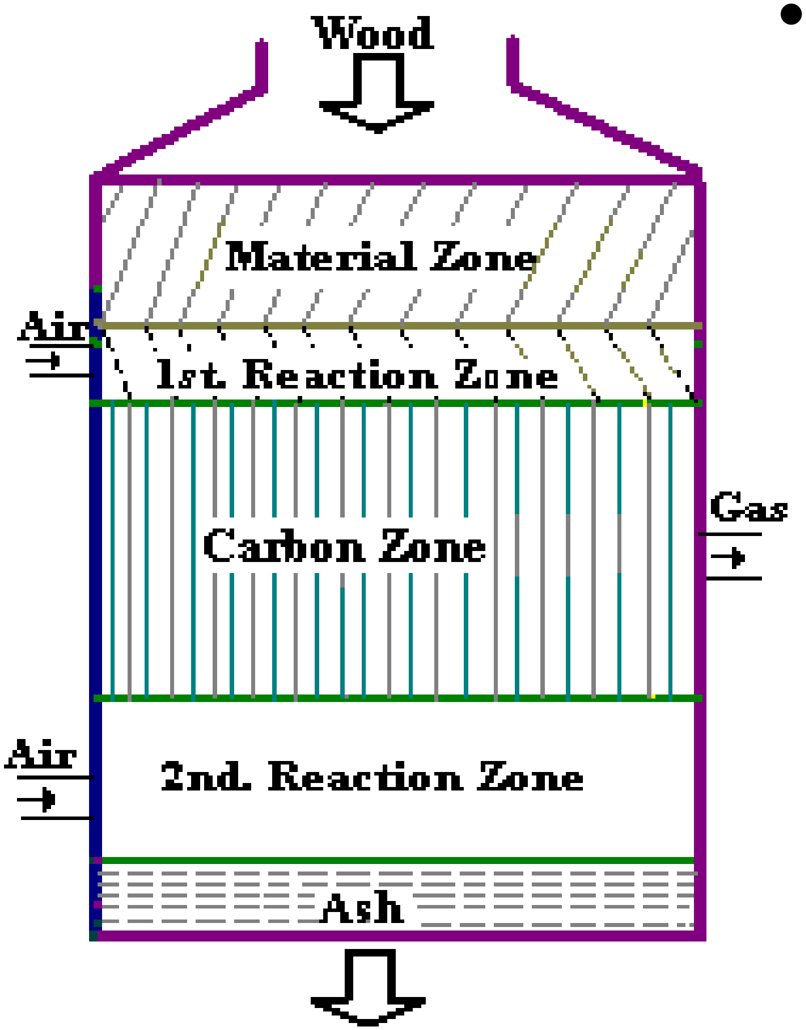



- Downdraft Gasifier

+ Very low tar gas [< 1 g/nm3]
+ Good gas CV [~5 MJ/nm3]
+ Simple gas train possible
+ Modular design
+ Simple construction and operation

- Limited scalability [0.5 MWe~ 500 kg/h]
- Precise fuel requirements [size, shape, moisture]
- Engine costs can be high relative to other costs
- Limited turndown

## Gasifier types



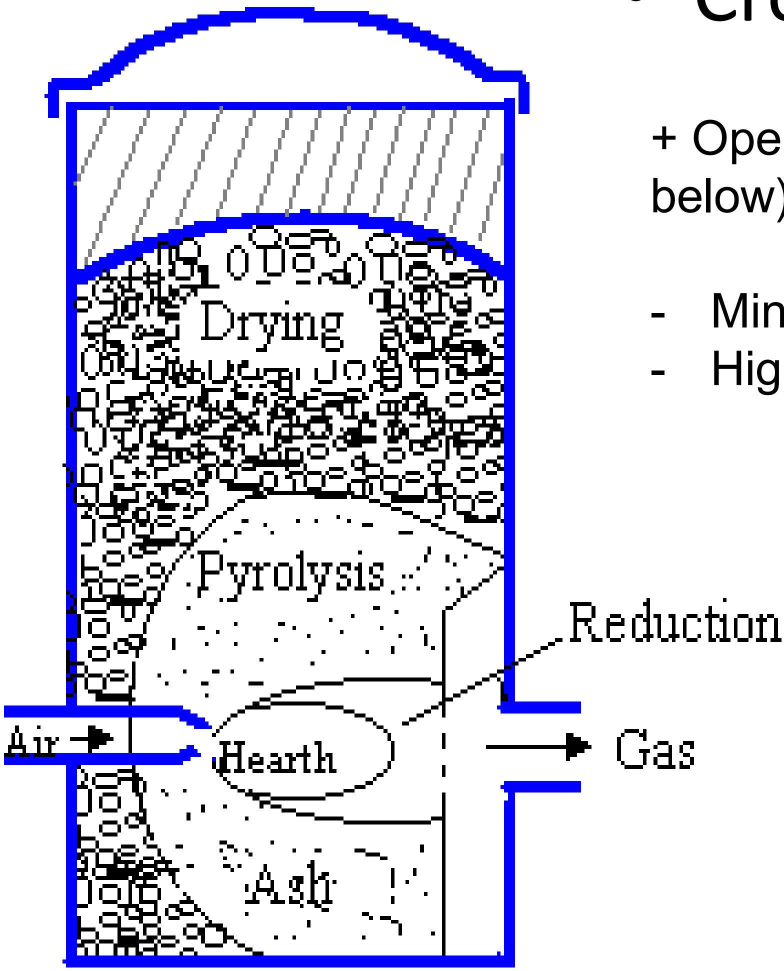

- Twin-fire Gasifier

+ Suitable for large electrical outputs [> 5-10 MWe]
+ More flexible in use of steam, air, steam/O2 mix
+ High gas CV – 8-12 MJ/nm3
+ High overall electrical efficiencies [gas turbine use]

- Complex design
- Limited turndown
- Stable operation difficult [DPs, gas flows]
- High tar levels in gas – extensive cleaning/catalytic cracking required [Ni based
or dolomites].
- Feed pretreatment to small particles

## Gasifier types

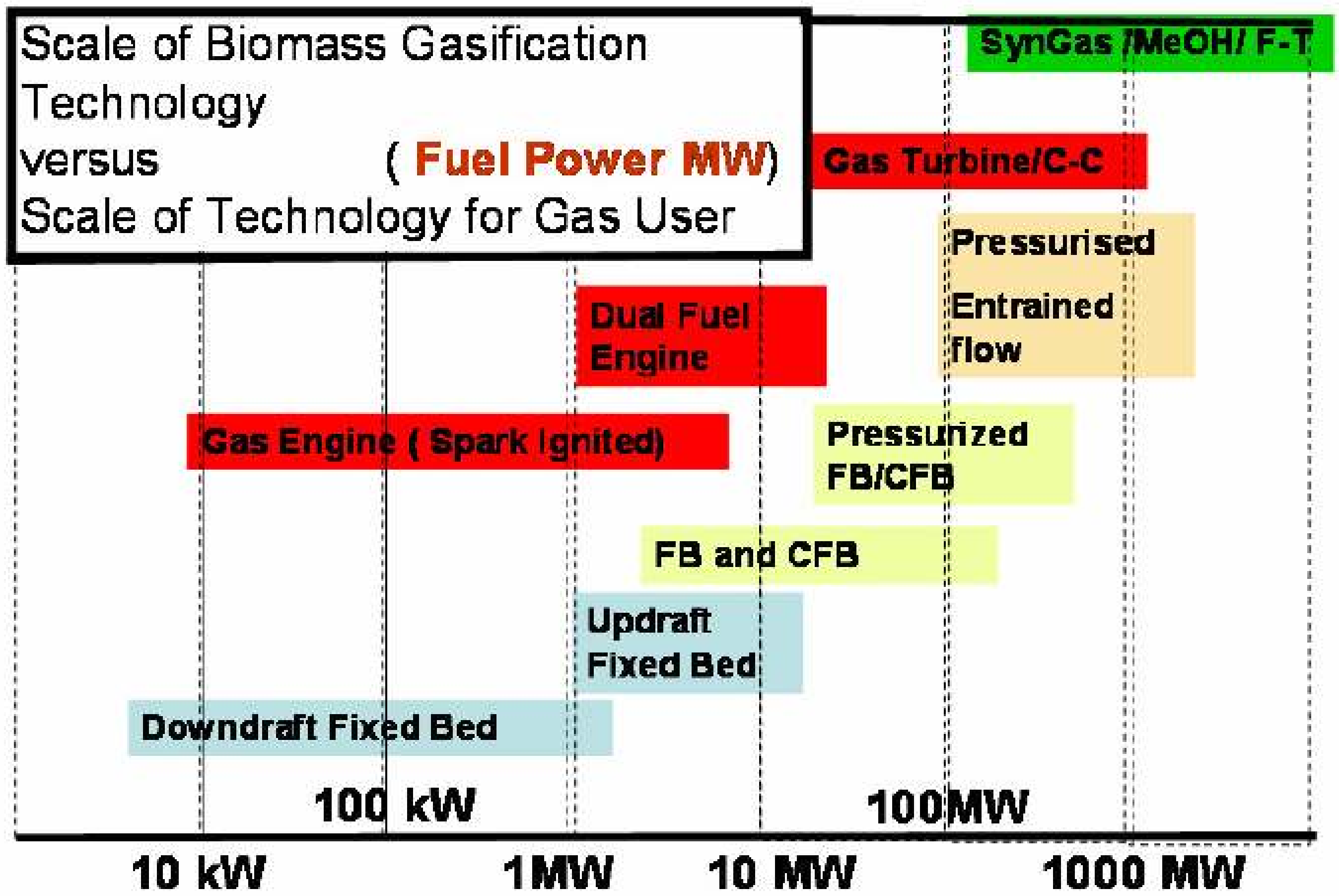
- Crossdraft Gasifier




+ Operable at very small scale (10kW and below)

- Minimum tar conversion capabilitites
- High exit gas velocity and temperature

# Gasification Technology scale output



# Example of gasification unit in UK

ITI Energy Ltd.
2 MWe CHP [2006]

Biomass Engineering Ltd.
250 kWe CHP [2004]

BASF Seal Sands [BGL]
30 MWth [since 2002]

Various plastic and nitrogen containing wastes

Global Energy Inc.[BGL] coal/sludge
273 and 400 MWth [2001 & 2002]

# Biomass Energy Conversions Technologies
# 2- Biochemical processes

# Anaerobic Digestion

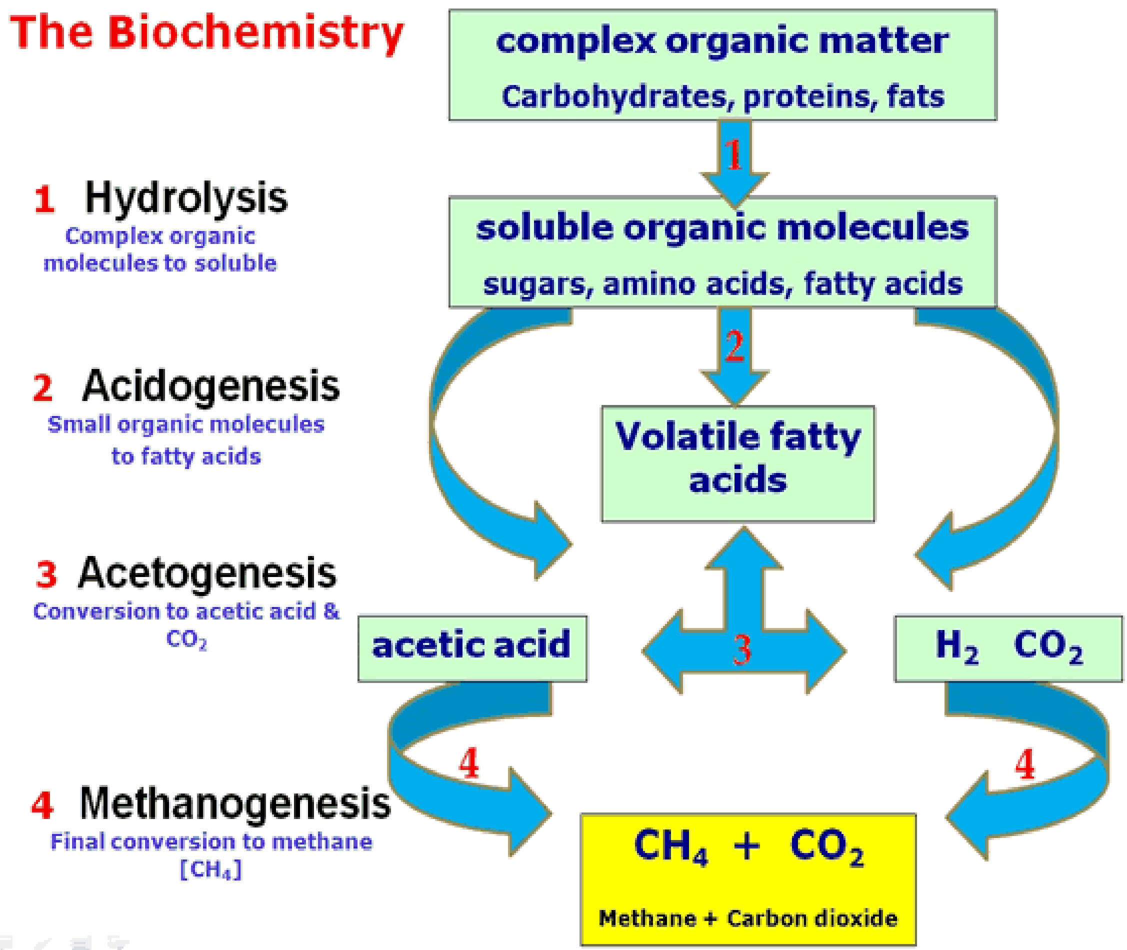
- AD is a series of biological processes in which microorganisms breakdown biodegradable material in the absence of oxygen
- End product of the process:

1. Biogas: a mixture of $CH_4$ and $CO_2$ mainly which is combusted to generate electricity and/or heat or processed into renewable natural gas and transportation fuel
2. Digested solid: residue from the digester, can be composted and applied as land amendment or used for dairy bedding
3. Nutrients: residue from liquid digestate, used in agriculture as fertilizer

- Various feedstock can be used:

Livestock manure, municipal wastewater solids, food waste, industrial wastewater and residuals, fats, and other organic waste streams

# Anaerobic Digestion Principle




- Initial **hydrolysis** of particulate matter and larger molecules
- Fermentation (**acidogenesis**) (formation of acids) generating primarily acetate but also other Volatile Fatty Acids (VFA)
- **Acetogenesis** (formation of acetate), Hydrogen is used as an electron acceptor
- **Methanogenesis**

Acetate → $CO_2$ + $CH_4$

(major pathway app. 70%)

$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

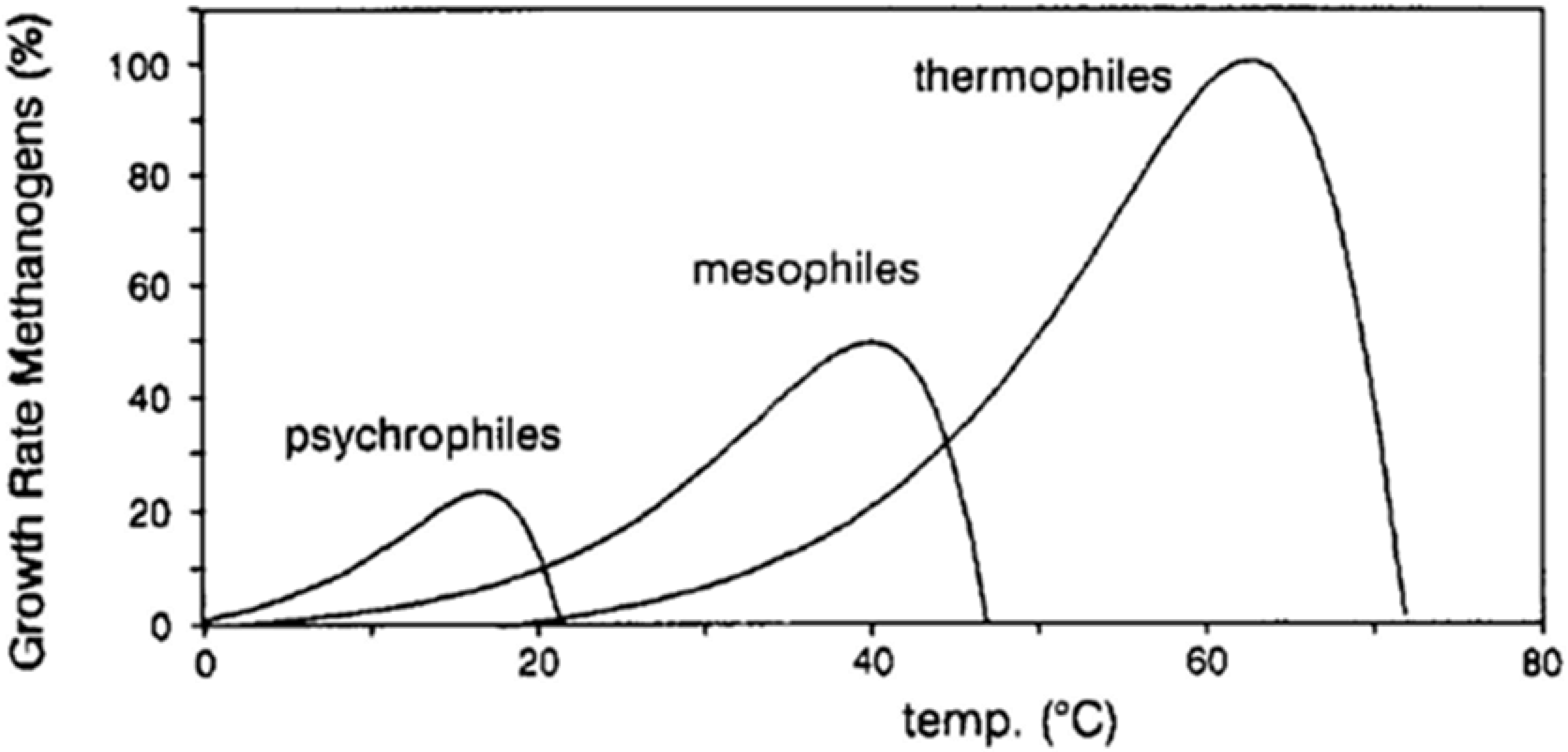
# Anaerobic Digestion

## Parameters and conditions influencing AD

| Parameters | Optimal conditions |
|---|---|
| Total solid content (TS) | Low (<10 %)<br>Medium (10-20 %)<br>High (20-40%) |
| Temperature | Mesophilic (20-45 °C)<br>Thermophilic (50-65 °C) |
| Retention time | 15-30 days for mesophilic<br>12-14 days for thermophilic |
| pH | Optimum between 6 – 7<br>Low pH inhibit acidogenesis stage<br>High pH is toxic for methane forming bacteria |
| Carbon to Nitrogen ratio (C:N) | Optimum between 20 – 30<br>High C:N → rapid N consumption → lower gas production<br>Low C:N → ammonia accumulation → toxicity |
| Organic loading rate (OLR) | High OLR → accumulation of inhibiting substances → low biogas yield |

# Anaerobic Digestion

**Effect of operating temperature**



# Anaerobic Digestion

## Biogas properties

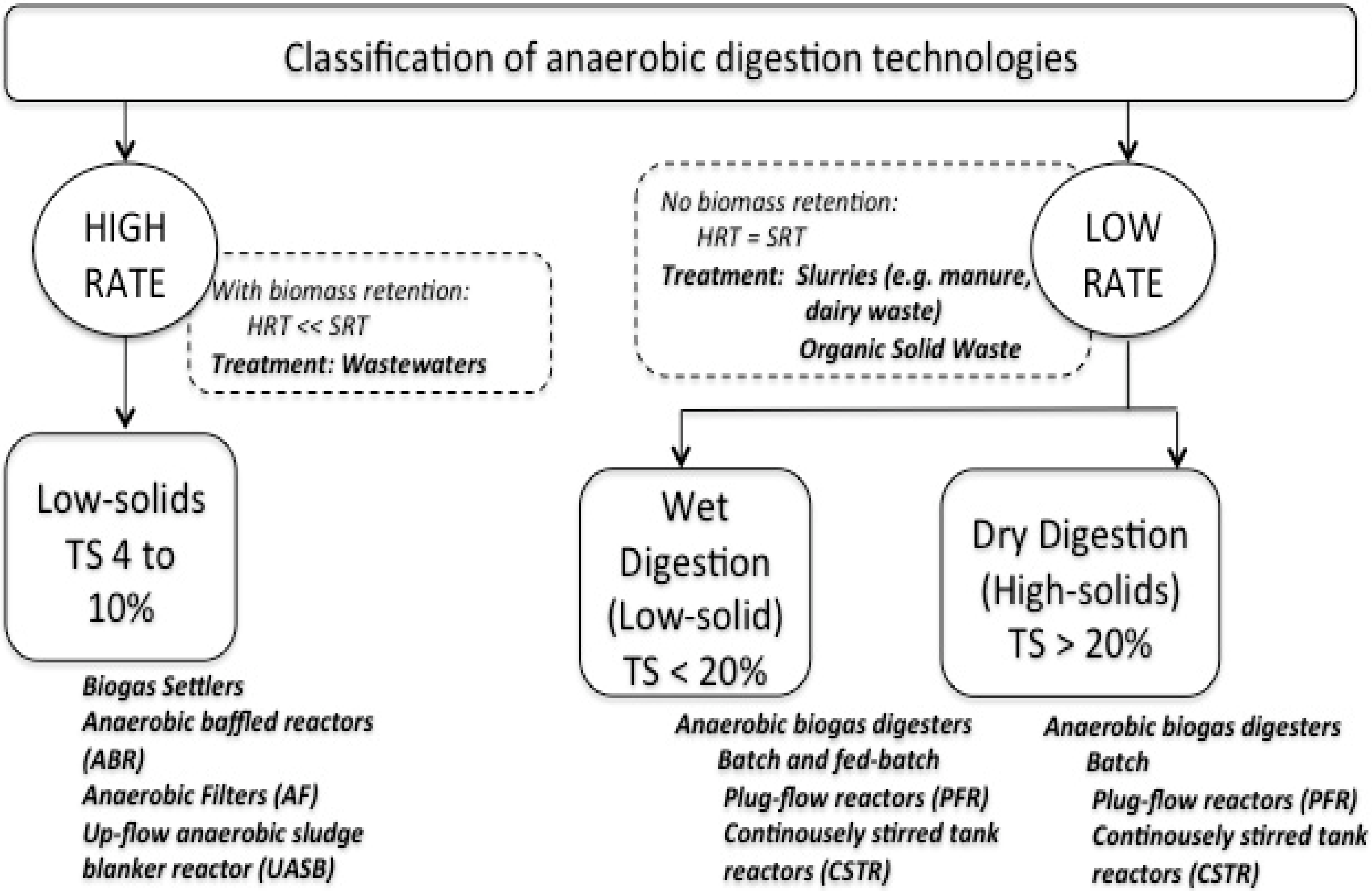
| Properties | $CH_4$ | $CO_2$ | $H_2$ | $H_2S$ | $NH_3$ | $N_2$ | $O_2$ | Raw Biogas (60% $CH_4$, 40% $CO_2$) |
|---|---|---|---|---|---|---|---|---|
| Molar percent [%] | 55-70 | 27-44 | < 1 | < 0.5 | < 0.05 | < 5 | < 2 | 100 |
| Calorific value [MJ.m-3] | 35.88 | - | 10.78 | 22.8 | - | - | - | 21.53 |
| Ignition temperature [°C] | 650 | - | 574 | 560 | - | - | - | 650-750 |
| Normal density [kg m-3] | 0.72 | 1.98 | 0.09 | 1.54 | 0.77 | 1.25 | 1.43 | 1.20 |
| Molar Mass [g mol-1] | 16.04 | 44.01 | 2.02 | 34.08 | 17.03 | 28.01 | 32.00 | 27.23 |

## Biogas potential of some biomass substrate

| Type of biomass | Biogas yield [$m^3/t$] |
|---|---|
| Beef slurry | 25 |
| Dairy waste | 55 |
| Cuttings from beet | 75 |
| Green waste | 110 |
| Biowaste | 120 |
| Fresh fat | 400 |
| Old fat | 800 |

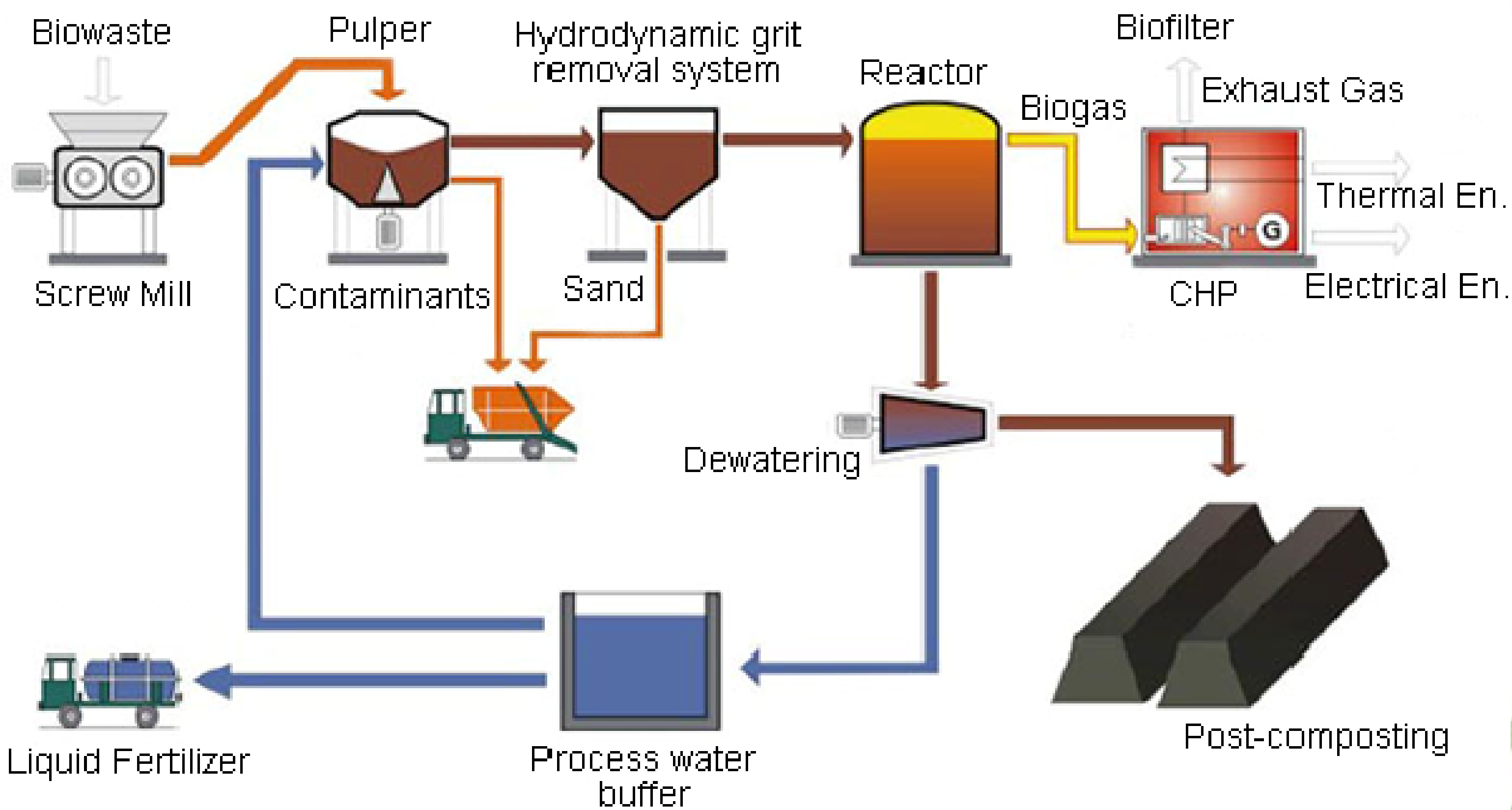
# Anaerobic Digestion

## Biogas properties



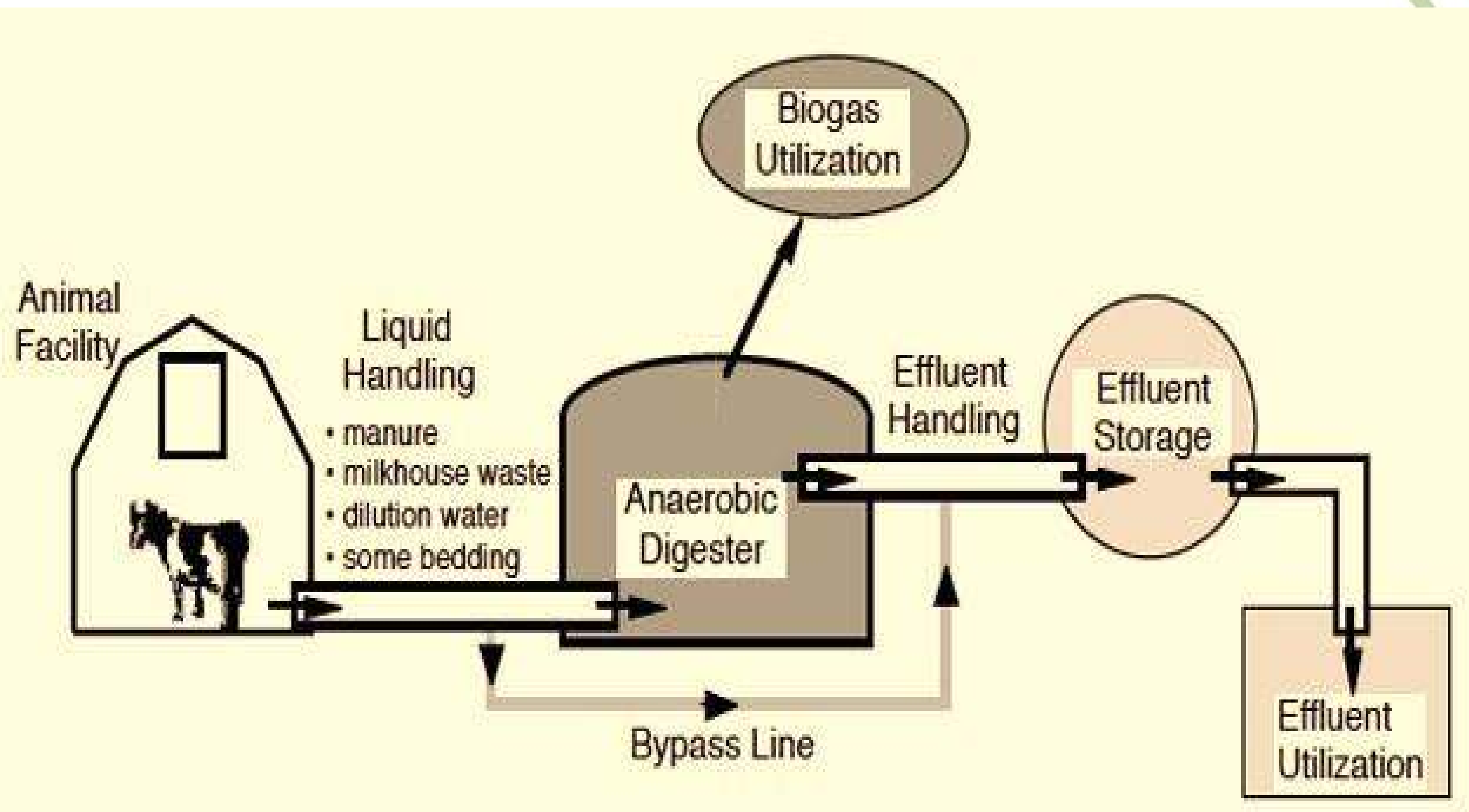
# Anaerobic Digestion

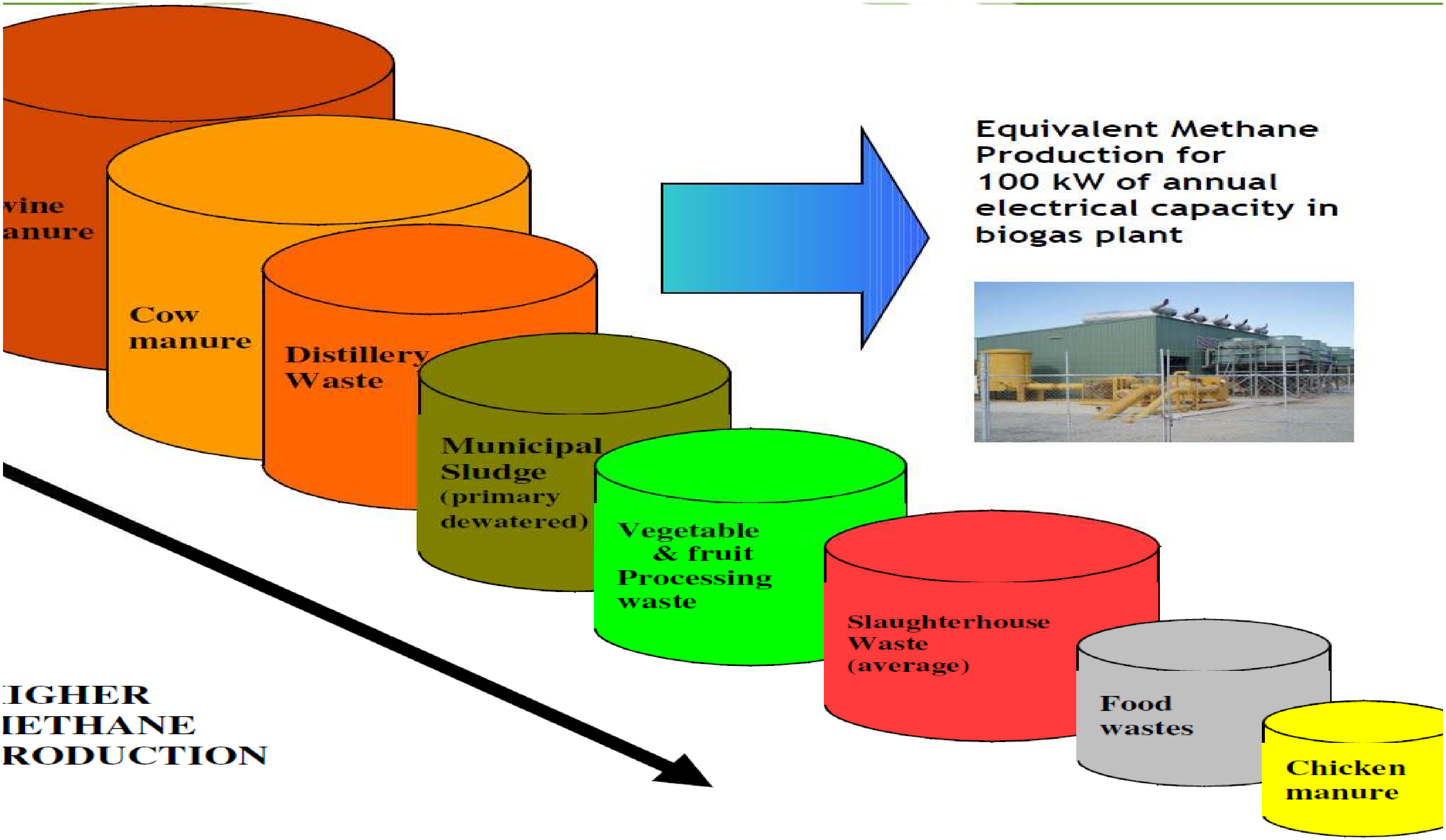
## Typical Biogas Power Plant



# Anaerobic Digestion

**Schematic of a typical agricultural AD system**






| | |
|---|---|
| Cow manure @ 18m3/ton | 12,000 tons = 100 kW |
| Swine manure @ 16m3/ton , | 14,000 tons = 100 kW |
| Distillery @ 30 m3/ton | 7,300 tons = 100 kW |
| Potato waste @ 39m3/ton | 5,600 tons = 100 kW |
| Municipal sludge @ 50-80m3/ton | 4,400 tons = 100 kW |
| Vegetable/fruit canning/pickling @ 100m3/ton | 2,200 tons = 100 kW |
| Slaughterhouse @ 100m3/ton | 2,200 tons = 100 kW |
| Household food waste @120 m3 CH4/ton | 1,800 tons = 100 kW |
| Chicken manure @ 130 m3/ton | 1,700 tons = 100 kW |

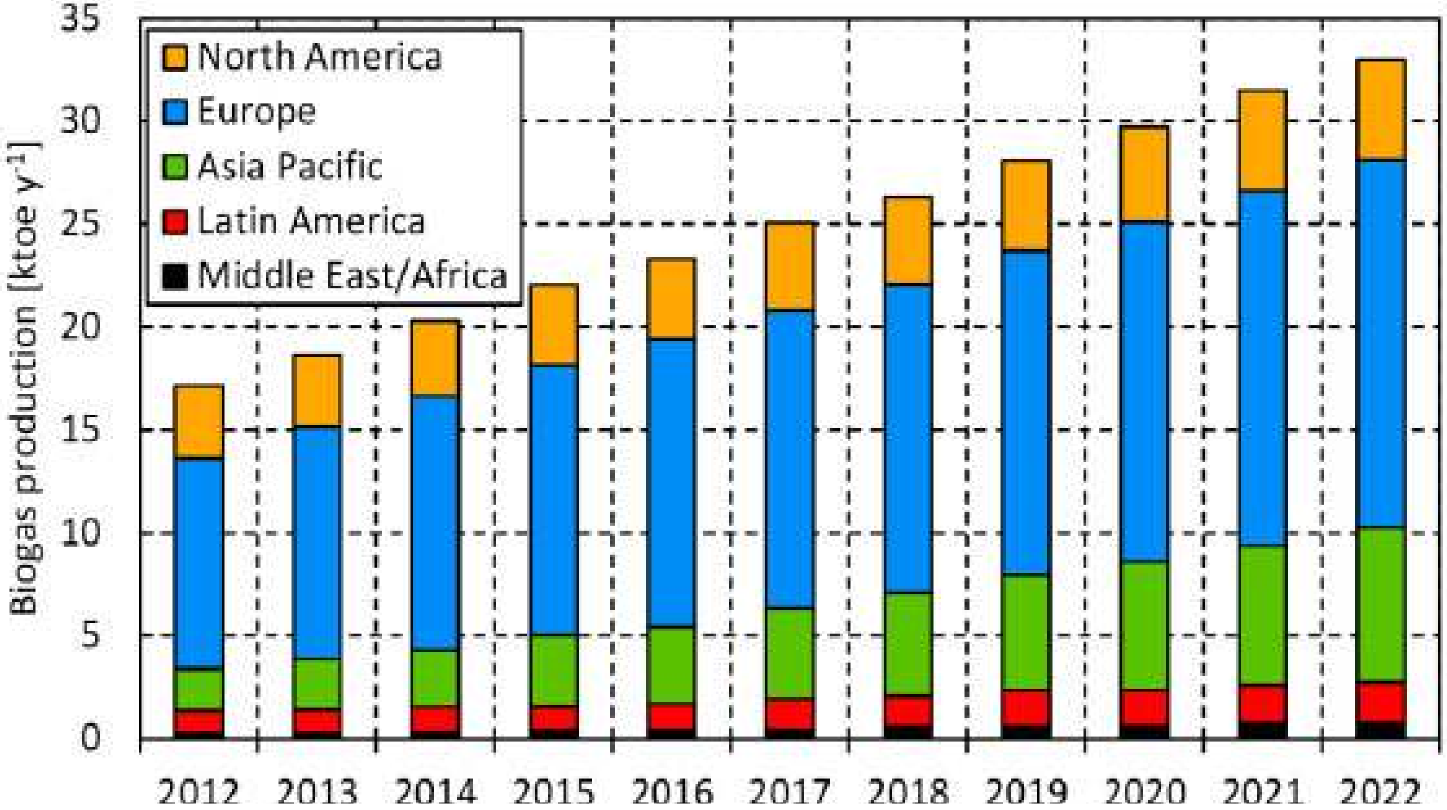
# Anaerobic Digestion

## SIZES OF BIOGAS PLANTS

| Category | Biogas Delivery | Size of Digester | Application |
|---|---|---|---|
| Very small Biogas plant | 0.65 $m^3$/day | - | For small family of 3 members having 2 cattle. |
| Small biogas plant | 2 $m^3$/day | - | For family of 6 members having 8 cattle. |
| Medium (family size) biogas plant | 3 $m^3$/day | 1.6 m dia, 4.2 m height | For family of 12 persons having 12 heads of cattle. |
| Large (farm size) biogas plant | 6 $m^3$/day | 3.3 m dia, 4.65 m height | For a farm having poultry diary etc., 20 cattle. |
| Very Large (community size) | 2600 $m^3$/day ($CO_2$ free) | 1000 $m^3$ | Cattle 1000 |

# Anaerobic Digestion

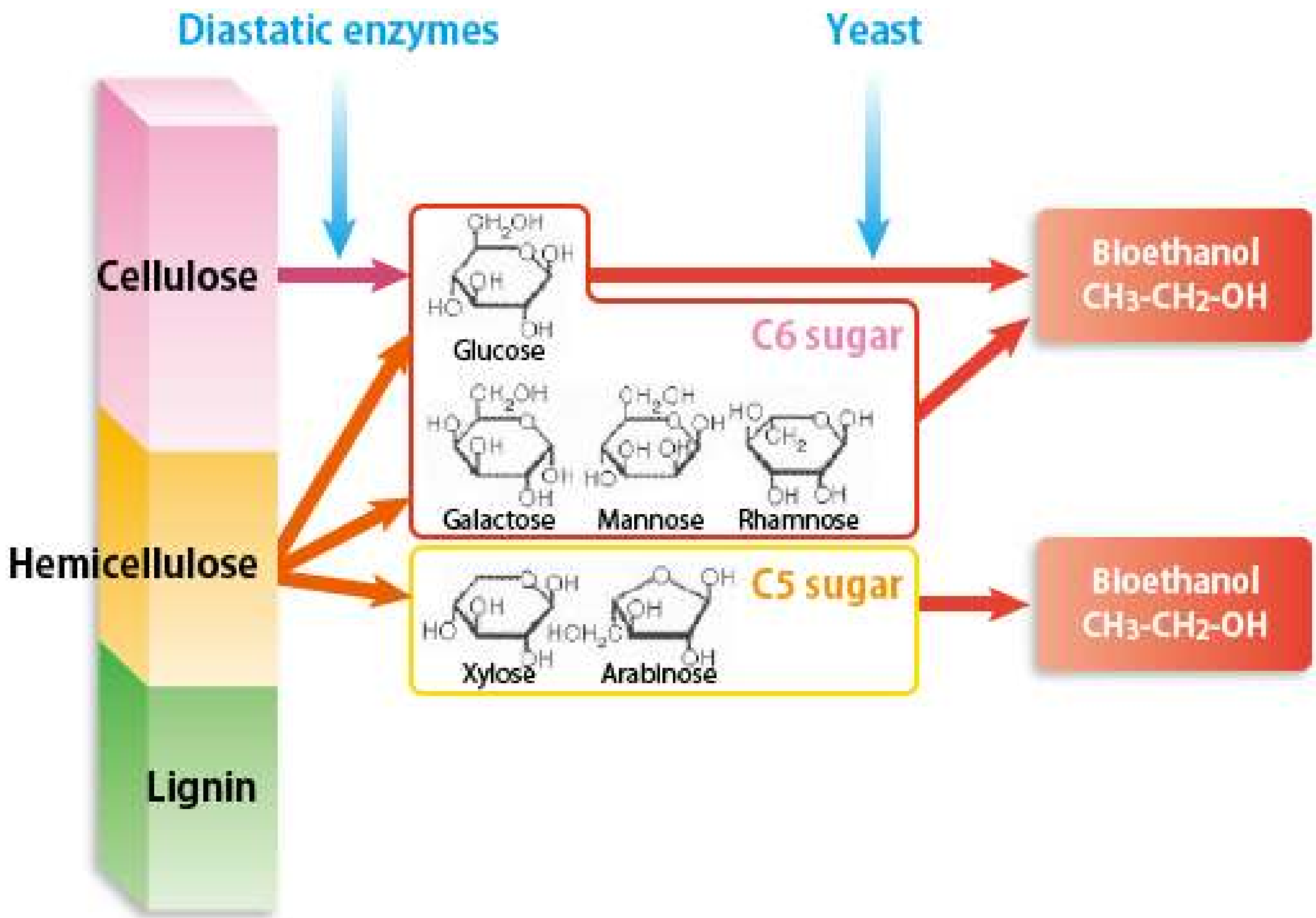
**Biogas Production at 2012 and trend to 2022 (Pike Research, 2012)**




**1 toe = 11.63 MWh**

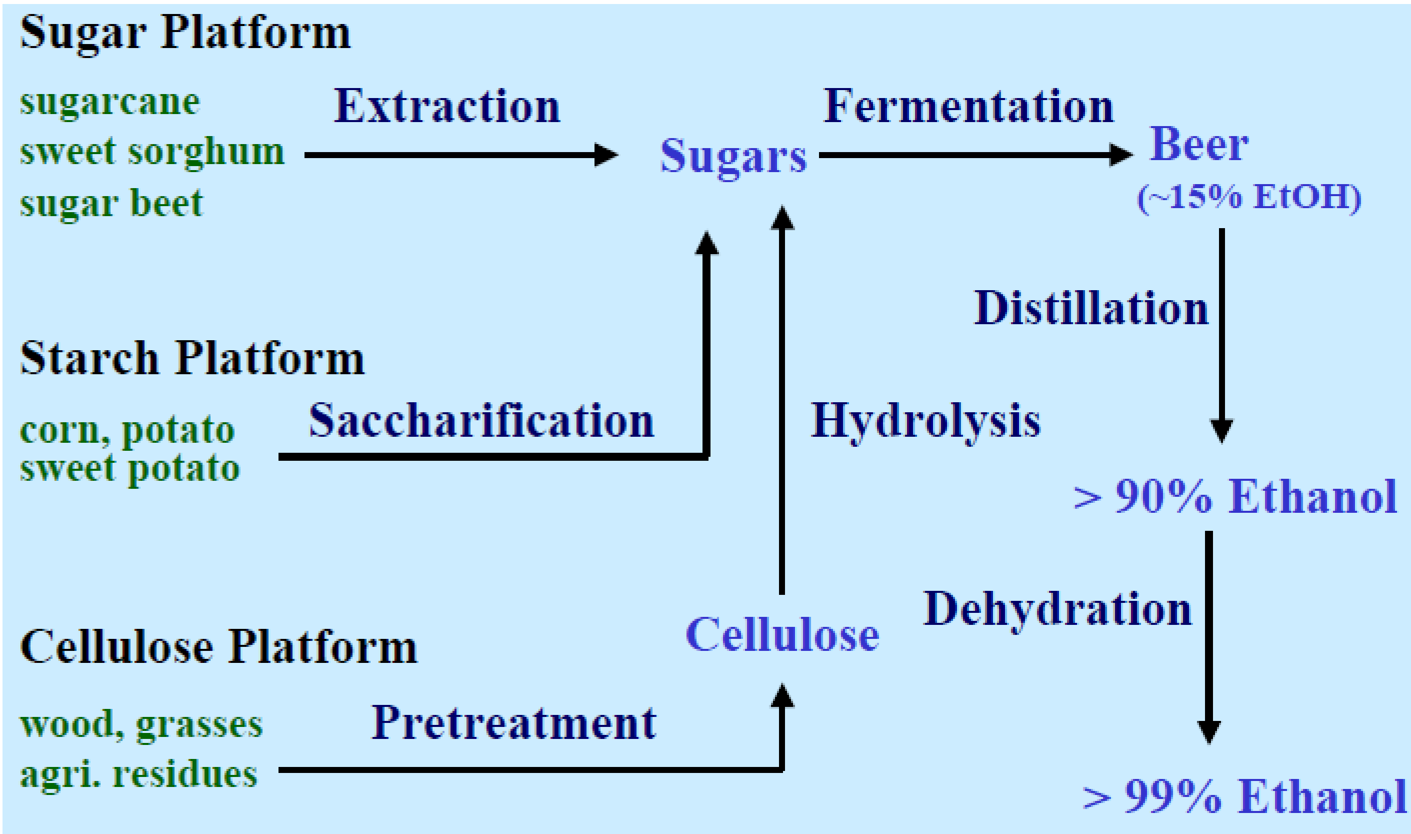
# Fermentation

## Bioethanol production process



# Fermentation

## Bioethanol production flow diagram




**Feedstock: corn, wheat, sugarcane, rice, potato, …**

# Conclusion

1. Biomass is a sustainable and reliable energy resource
2. The growth rate of biomass energy use is about 1 % each year
3. Technological barriers have to be overcame in order to promote the bioenergy development:
   – Upgrading the bio-fuel quality by extracting harmful species especially for biogas and syngas (ammonium, sulfur compounds, silicon based compounds, particulate, …)
   – Enhance the reaction mechanism for both AD and gasification processes

# Thank you