BIOMASS and BIOFULS – Part 1

Biomass properties and classification

Prof. Marco Fiala

Department of Agricultural and Environmental Sciences. Production, Landscape, Agroenergy (DiSAA)

☎ +39 02 503 16868  ⚪️ marco.fiala@unimi.it
PHOTOSYNTHESIS vs. OXIDATION: The broken equilibrium

1° PHASE = Production > Consumption → STORAGE
2° PHASE = Production = Consumption → BALANCE
3° PHASE = Production < Consumption → TAKING OFF

RADIATION (light, heat)

DIRECT (hydro, wind, tide)

CO₂

O₂

H₂O

Cₓ - Hᵧ - O₂

BIOMASS

MINERALS

PHOTOSYNTHESIS

200 billion t/year of C = 70000 Mt⁻oe

OXIDATION (combustion, respiration)

ENERGY

ELECTRICAL

MECHANICAL

THERMAL

FOOD & FEED

FUEL

NO RENEWABLE Fossil Sources

Marco Fiala (UniMI - DiSAA)
Biomass composition: starch, cellulose, hemicellulose e lignin.

ENERGY STORED INTO CHEMICAL BONDS =
<table>
<thead>
<tr>
<th>ORIGIN</th>
<th>BIOMASS TYPE (sector)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant (vegetable)</td>
<td>1 – Agricultural by-products (food, no-food crops) (agriculture → crop cultivation)</td>
</tr>
<tr>
<td></td>
<td>2a – Erbaceous energy crops (agriculture → crop cultivation)</td>
</tr>
<tr>
<td></td>
<td>2b - Arborescent energy crops (agriculture → crop cultivation)</td>
</tr>
<tr>
<td></td>
<td>3 – Wood and residues, wood derivates (forestry; wood industry)</td>
</tr>
<tr>
<td></td>
<td>Wood waste (end-use wood)</td>
</tr>
<tr>
<td>Animal</td>
<td>4 – Animal wastes (agriculture → animal breedings)</td>
</tr>
<tr>
<td>Household</td>
<td>5 – Organic Fraction Municipal Solid Waste OFMSW (urban areas)</td>
</tr>
<tr>
<td>Industrial</td>
<td>6 – Dry (lignocellulosic) residues (industry → agri-food)</td>
</tr>
<tr>
<td></td>
<td>7 – Wet (fermentable) residues (industry → agri-food)</td>
</tr>
</tbody>
</table>

**Examples of Biomass Types:**
- Straw (cereals)
- Pruning residues (grape, olive)
- Oil Seeds (sunflower, rape)
- Ligno-cellulosic (miscantus)
- Grass (corn)
- Animal wastes
- Organic Fraction Municipal Solid Waste (OFMSW)
- Dry (lignocellulosic) residues
- Wet (fermentable) residues
- Slurry (pigs, cattle)
- Manure (cattle; chickens)
- Wood chips (poplar SRF)
- Wood logs and chips (forestry)
- Pellet, residues (industry)
- Grape skins/Olive oil residues
- Leaves and stems (fresh vegetable)
- Husk, dry skins (rice)
- Shell/fruit stones (almond, nut)
The fresh biomass (FM) is always composed by:
- **a mass of water** (Moisture Content, MC)
- **a dry mass** (Total Solid, TS or Dry Matter, DM → C, N, O, H, S, ash)
**MOISTURE CONTENT (MC; %) → free water** inside biomass

Moisture Content on wet basis (MC) → related to fresh mass $m_{FM}$ (range: from 4-5% to 90-92%)

Moisture Content on dry basis ($MC_{DM}$) → related to dry mass $m_{DM}$

Water is contained in two forms: (i) **bound** to the molecular structure, (ii) **free** within cells and plant tissues; the amount of contained water depends on climatic conditions, period of harvest and conservation processes.

\[
MC = \frac{m_{H2O}}{m_{FM}} = \frac{m_{H2O}}{m_{DM} + m_{H2O}}
\]

\[
MC_{DM} = \frac{m_{H2O}}{m_{DM}} = \frac{MC}{1 - MC}
\]

**EXAMPLE**: a fresh wood mass of $m_{FM} = 2.3$ kg has a moisture content (wet basis) of $MC = 45\%$. Consequently, the dry matter is $DM = 55\%$ and water mass (kg) and the dry mass (kg) are, respectively:

\[
m_{H2O} = m_{FM} \times MC = 2.3 \times 0.45 = 1.035 \text{ kg}
\]

\[
m_{DM} = m_{FM} - m_{H2O} = 2.3 - 1.035 = 1.265 \text{ kg}
\]

\[
MC_{DM} = \frac{m_{H2O}}{m_{DM}} = \frac{1.035}{1.265} = 0.818 = 81.8\%
\]

\[
MC_{DM} = \frac{MC}{1 - MC} = \frac{0.45}{0.55} = 0.818 = 81.8\%
\]

**CARBON-NITROGEN RATIO (C/N; -)**

Ratio between carbon and nitrogen content of biomass dry mass (range: from 20-30 to 100-120)

In biomass derived from plants indicates the **biomass lignification degree**, while in animal waste (manure, slurry), it depends of **animal species, diet, farm characteristics and type of animal waste management**.
DENSITY ($\rho_{MC}; \text{ kg/m}^3 \text{ FM}$)

Mass ($m_{FM}; \text{ kg FM}$) contained in the unit of volume ($V_b; \text{ m}^3$).

It depends on moisture content: the greater the MC, the higher the $\rho_{MC}$. (→ increase of both the fresh mass and – slightly - the volume). Until full water absorption, the mass grows proportionally to MC, while the volume can be considered practically constant → $\rho_{MC}$ must always be referred to MC.

Literature very often refers to biomass density as dry biomass density ($\rho_0; \text{ kg/m}^3 \text{ DM}$).

EXAMPLE: the dry biomass density of *robinia* wood is $\rho_0 = 650 \text{ kg/m}^3 \text{ DM}$. At the time of cutting its moisture content is $MC = 45\%$. Consequently, the density is:

$$\rho_{MC} = \frac{\rho_0}{(1 - MC)} = \frac{650}{(1 - 0.45)} = 1182 \text{ kg/m}^3$$
Biomass chemical and physical properties: bulk density

Bulk Density ($\gamma_{MC}$; kg/m$^3$ FM)

Mass ($m_{FM}$; kg FM) contained in the unit of volume also considering the empty spaces ($V_a$; m$^3$).

$$\gamma_{MC} = \frac{m_{FM}}{V_a}$$

Directly related to the technical aspects concerning biomass storage and/or handling (volumes, and transport costs). Extremely variable parameter, depending on the biomass moisture content and its final collection and/or packaging methods.

<table>
<thead>
<tr>
<th>BIOMASS</th>
<th>PREPARATION</th>
<th>BULK DENSITY</th>
<th>DIMENSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals straw, herbaceous stem</td>
<td>Raw material</td>
<td>30-40</td>
<td>-</td>
</tr>
<tr>
<td>and leaves energy crops</td>
<td>Small bales (prismatic)</td>
<td>80-120 (stacked)</td>
<td>$V = 0.1-0.2$ m$^3$</td>
</tr>
<tr>
<td></td>
<td>Cilindric bales</td>
<td>120-180 (stacked)</td>
<td>$V = 1.5-3.0$ m$^3$</td>
</tr>
<tr>
<td></td>
<td>Big bales (prismatic)</td>
<td>120-180 (stacked)</td>
<td>$V = 2.0-4.0$ m$^3$</td>
</tr>
<tr>
<td></td>
<td>Chopped</td>
<td>150-250 (piled)</td>
<td>10-250 mm</td>
</tr>
<tr>
<td>Mais stem and leaves</td>
<td>Raw material</td>
<td>50-60 (piled)</td>
<td>-</td>
</tr>
<tr>
<td>Pruning residues</td>
<td>Raw material</td>
<td>50-70</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Small cilindric bales</td>
<td>150-210 (stacked)</td>
<td>$V = 0.6-0.8$ m$^3$</td>
</tr>
<tr>
<td></td>
<td>Chipped</td>
<td>200-300 (piled)</td>
<td>1-100 mm ; $V = 2.5 \times 10^3$ dm$^3$</td>
</tr>
<tr>
<td>Wood</td>
<td>Logs</td>
<td>600-700 (stacked)</td>
<td>300-1000 mm ; $V = 1.5-15$ dm$^3$</td>
</tr>
<tr>
<td></td>
<td>Chipped</td>
<td>200-300 (piled)</td>
<td>1-100 mm ; $V = 2.5 \times 10^3$ dm$^3$</td>
</tr>
<tr>
<td>Sawdust</td>
<td>Milling process</td>
<td>120-180 (piled)</td>
<td>1-5 mm</td>
</tr>
<tr>
<td>Mais silage</td>
<td>Cut</td>
<td>450-750 (pressed)</td>
<td>10-25 mm</td>
</tr>
<tr>
<td></td>
<td>350-400 (piled)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pellet</td>
<td>Extrusion process</td>
<td>800-900 (piled)</td>
<td>$\emptyset &lt; 25$ mm</td>
</tr>
<tr>
<td>Briquettes</td>
<td>Extrusion process</td>
<td>190-340 (piled)</td>
<td>$\emptyset &gt; 25$ mm ; $V = 1-1.5$ dm$^3$</td>
</tr>
<tr>
<td>Fruit shells</td>
<td></td>
<td>250-450 (piled)</td>
<td>5-20 mm</td>
</tr>
<tr>
<td>Fruit kernels</td>
<td></td>
<td>350-550 (piled)</td>
<td>5-20 mm</td>
</tr>
<tr>
<td>Olive oil residues</td>
<td>Compression. centrifugation</td>
<td>400-500 (piled)</td>
<td>1-5 mm</td>
</tr>
<tr>
<td>Grape residues</td>
<td>Compression process</td>
<td>250-500 (piled)</td>
<td>1-5 mm</td>
</tr>
<tr>
<td>Rice/cereal/husk</td>
<td>Separation process</td>
<td>130-140 (piled)</td>
<td>1-5 mm</td>
</tr>
<tr>
<td>Animal slurry</td>
<td>Collected/moved by pumps</td>
<td>1000 (piled)</td>
<td>-</td>
</tr>
<tr>
<td>Animal manure</td>
<td>Collected/moved by mechanical devices</td>
<td>500-650 (piled)</td>
<td>-</td>
</tr>
</tbody>
</table>
Biomass chemical and physical properties: heating values (GHV, LHV)

**GROSS HEATING VALUE** (GHV; J/kg DM; kcal/kg DM; kcal/m³ N)

Thermal Energy developed from complete combustion of:
- 1 kg liquid or solid fuel
- 1 m³ N gaseous fuel (normal cubic meter → p = 1 bar, T = 0 °C) or 1 m³ S (standard cubic meter p = 1 bar, T = 20 °C)

It takes into account the energy due to vapor condensation generated during the complete fuel oxidation

\[ C_x H_y O_z + O_2 \rightarrow CO_2 + H_2 O + \text{ENERGY} \]

\[ GHV = 0.35 \cdot [C] + 1.18 \cdot [H] + 0.10 \cdot [S] - 0.02 \cdot [N] - 0.10 \cdot [O] - 0.02 \cdot [Ash] \] (MJ/kg)

**LOWER HEATING VALUE** (LHV; J/kg DM; kcal/kg DM; kcal/m³ N)

Determined subtracting the heat of vaporization of the water vapor from the GHV. The energy required to vaporize the water contained in the biomass is not released as useful heat (lost at the chimney inside the smokes).

<table>
<thead>
<tr>
<th>BIOMASS</th>
<th>MC (%)</th>
<th>YIELD (t/ha FM)</th>
<th>ASH (%)</th>
<th>LHV (kWh/kg s DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat straw</td>
<td>14-20</td>
<td>3-6</td>
<td>7-10</td>
<td>4.8-4.9</td>
</tr>
<tr>
<td>Rice straw</td>
<td>20-30</td>
<td>3-5</td>
<td>10-15</td>
<td>4.3-4.4</td>
</tr>
<tr>
<td>Corn stalks</td>
<td>40-60</td>
<td>4.5-6</td>
<td>5-7</td>
<td>4.6-5.0</td>
</tr>
<tr>
<td>Pruning residues</td>
<td>45-55</td>
<td>3-4</td>
<td>2-5</td>
<td>5.0-5.1</td>
</tr>
<tr>
<td>Wood (robinia, 20-30 yrs)</td>
<td>40-45</td>
<td>30-75</td>
<td>2-3</td>
<td>5.0-5.1</td>
</tr>
<tr>
<td>Carpino (30-40 anni)</td>
<td>40-45</td>
<td>55-100</td>
<td>1-2</td>
<td>4.9-5.0</td>
</tr>
</tbody>
</table>
Biomass chemical and physical properties: heating values (NHV)

**NET HEATING VALUE** (NHV; J/kg FM; kcal/kg FM; kcal/m³)
LHV to which is removed the heat necessary to evaporate the free water (m_H2O) inside biomass. Practically, NHV is heat recoverable from the fresh biomass, releasing combustion smokes into the atmosphere.

\[
\text{NHV} = \text{LHV} \times (1 - \text{MC}) - c_{\text{EV}} \times \text{MC}
\]

- \( c_{\text{EV}} = \text{heat of H}_2\text{O vaporization} \)
  - \( 2261 \text{ kJ/kg} \text{ H}_2\text{O} = 540 \text{ kcal/kg} \text{ H}_2\text{O} = 0.628 \text{ kWh/kg} \text{ H}_2\text{O} \)

**EXAMPLE**: The wood of *robinia* has a Lower Heating Value \( \text{LHV} = 5.0 \text{ kWh/kg DM (4300 kcal/kg DM)} \); the Net Heating Value at the cut (fresh wood \( \rightarrow \text{MC} = 45\% \)) is:

\[
\text{LHV} = 4300 \text{ kcal/kg DM}
\]
\[
\text{MC} = 45\%
\]
\[
\text{DM} = 55\%
\]

\[
\text{LHV} \times (1 - \text{MC}) = 4300 \times (1 - 0.45) = 2365 \text{ kcal}
\]
\[
-540 \times \text{MC} = -540 \times 0.45 = -243 \text{ kcal}
\]

\[
\text{NHV} = 2122 \text{ kcal/kg FM}
\]
The sale of lignocellulosic biomass (example: wood) is "by weight". Knowing the moisture content is therefore crucial to buy energy and not water.
Biomass and energy conversion processes: general scheme

BIOMASS

DRY → ligno-cellulosic

Combustion

Pyrolysis

Gasification

Peroxidation

Extraction

WET → fermentable

Alcoholic fermentation

Methanic fermentation

Bio-fuels (liquids or gases)

Charcoal (char)

Syngas

Bio-oils (tar)

Gas (CO + H₂ + CH₄ = 22-30%)

(a) Vegetable Pure Oil
(b) Biodiesel

Bio-ethanol

Biogas (CH₄ = 50-60%)

THERMAL EN. (H₂O < 100°C)

THERMAL EN. (H₂O > 100°C)

ENGINE (Otto Cycle)

TURBINE (Rankine Cycle)

MECHANICAL ENERGY

ELECTRIC GENERATOR

ELECTRICITY
Biomass-to-energy: oil equivalent

**BIO-FUELS**

- **Bio-diesel**: 1.2 kg $\cong$ 1.3 Liters
- **Bio-ethanol**: 1.6 kg $\cong$ 1.9 Liters
- **Biogas**: 2.1 kg $\cong$ 1.7 m$^3_N$

**LIGNOCELLULOSIC BIOMASS**

$\cong$ 2.0-2.5 kg FM

$1 \text{ kg}_{oe} = 10000 \text{ kcal}$
LIGNOCOMMULLOSIC BIOMASS $\rightarrow$ combustion, gasification, pyrolysis
Biomass energy parameters → Type A

PLANT DERIVED, LIGNOCELLULOSIC, GROWTH FUNCTIONS → (herbaceous and tree species: leaves, steams, branches)

Essentially made by: cellulose (50% DM, 3900 kcal/kg DM); hemicellulose (10-30% DM; 3000 kcal/kg DM); Lignin (20-30% DM, 6000 kcal/kg DM). Other simpler organic compounds (resins, fats, oils, waxes, starches, sugars, proteins, tannins, pigments, alkaloids, etc.) and inorganic materials (Na, K, Mg, Ca, Cd, Zn, As, Pb, S, Cl, N, P, Si, Al etc.)

BASIC ENERGY PARAMETERS

C/N Ratio > 30 → Lower Heating Value f (C%): 4.5-5.2 kWh/kg DM
MC = 25-45% → Net Heating Value f (1/MC): 1.8-2.5 kWh/kg DM
Ash (2-10% DM), frequently low melting point (T < 1000 °C)
### Biomass → energy parameters → Type A

#### AGRICULTURAL BY-PRODUCTS

- **STRAW** → **cereals** (wheat, rice, corn), **oil crop** (sunflower). Leaves and stems that, when harvesting the main product, are usually left in the field;
- **WOODY** → **pruning residues** (grape, olive, fruit trees). From winter cut operations, made to shape and/or balance the plants grown according to the various cultivation systems in use.

#### INDUSTRIES RESIDUES and WASTE

- **RESIDUES** → **fruit-processing** (shell and stones; **olive oil** (olive oil pomace; virgin and exhausted); **wine** (grape resiseses)
- **RESIDUES** → **wood-processing** (bark, chips and shavings, sawdust)

#### HERBACEOUS ENERGY-CROPS

- **STALKS & LEAVES** → **poli-annual cycle crops** (miscanthus, giant cane, etc.)
- **GRAINS** → **cereals** (wheat, rice, corn)

#### TREE SPECIES ENERGY CROPS

- **WOOD CHIPS** → **Short Rotation Coppice (SRC)** of poplar, eucalyptus, robinia (two or five years cut frequency).

#### WOOD and WOOD DERIVED PRODUCTS

- **LOGS or CHIPPED WOOD** → **forestry** (coppice and tall trees)
- **RESIDUES (END-USE WOOD)** → **different origins** related to human activities
- **DERIVED PRODUCTS** → specialized industries for extrusion products (pellets, briquettes)

---

**Type A**

ON REPORT TABLES SPECIFIC PARAMETERS ARE INDICATED
FERMENTABLE BIOMASS ➔ methanic fermentations

Type B and C
**Type B**

**PLANT DERIVED, FERMENTABLE, GROWTH FUNCTIONS**

(herbaceous: leaves, steams)

Composed mainly of **cellulose** and **hemicellulose**, poorly lignified. Other simpler **organic compounds** (organic extracts) and inorganic material (Na, K, Mg, Ca, Cd, Zn, As, Pb, S, Cl, N, P, Si, Al).

**BASIC ENERGY PARAMETERS**

- C/N Ratio < 30
- MC = 65-80%
- Ash (1-2% DM)
- VS: 85-95% TS; biogas yield: 500-700 m$^3$/t SV
- $\text{CH}_4 = 55-65\%$ vol. → LHV biogas = 5.0-6.2 kWh/m$^3$$_N$

**Type C**

**ANIMAL DERIVED, FERMENTABLE**

(slurry and manure)

Livestock effluents, a mix of: **excreta** (feces and urine), **water, feed residues** and **litter** (straw, sawdust, husk, etc.) when used. Extremely variable composition according to: (i) animal species (cows, pigs, poultry), (ii) breeding methods, (iii) characteristics of the feed (iv) waste management system.

**BASIC ENERGY PARAMETERS**

- VS: 65-85% TS (slurries), 75-90% TS (manures); biogas yield: 300-550 m$^3$/t SV;
- $\text{CH}_4 = 50-65\%$ vol. → LHV biogas = 4.8-6.2 kWh/m$^3$$_N$
### HERBACEOUS ENERGY-CROPS

- **SILAGES** → *corn, wheat, triticale* (waxy maturation) *sorghum* (anaerobic co-digestion).

### ANIMAL WASTE

- **SLURRY** → liquid, fluid or dense consistency, *TS* < 20%, moved by a **pump** (up to 16% TS);
- **MANURE** → thick, semi-solid or solid consistency, *TS* ≥ 20%, moved by a **shovel**.

### INDUSTRIES RESIDUES and WASTE

- **RESIDUES** → *fruit-processing* (pulps and peel); *vegetable-processing* (tomatoes and potatoes peel); *olive oil* (vegetation water);
- **WASTE** → *milk processing* (whey);
- **WASTE** → *meat processing* (blood, fat, whey, gut, stomach contents, etc.).

### DOMESTIC WASTE

- **WASTE** → *Organic Fraction of Municipal Solid Waste (OFMSW).*

---

**Type B and C**

**ON REPORT TABLES SPECIFIC PARAMETERS ARE INDICATED**
SEEDS $\rightarrow$ oil extraction, alcholic fermentation, combustion
PLANT DERIVED, OIL, REPRODUCTIVE FUNCTIONS (herbaceous and tree species: seed)

Oleaginous species seeds.

TROPICAL CLIMATE (Southeast Asia, India, China, Africa):
- palm (*Elaeis guineensis*) → tree species with edible seeds
- jatropha (*Jatropha curcas*) and pongamia (*Pongamia pinnata*) → herbaceous/shrubby species, non-edible seeds;

TEMPERATE CLIMATE (Central-South Europe, North America):
- rapeseed (*Brassica napus*), sunflower (*Heliantus annuus*), castor (*Ricinus communis*), soybean (*Glicine max*) herbaceous, with edible seeds

**BASIC ENERGY PARAMETERS**

Oil content: 25-45% FM; LHV oil (SVO): 10,0-11,0 kWh/kg

**Oil extraction (SVO)**

**Soil competition**

**Type D1**

On report tables specific parameters are indicated.

Marco Fiala (UniMI - DiSAA)
**Cereals** seeds (grains).

**TROPICAL CLIMATE** (Central-South Europe, North America):
- corn, wheat and barely,

**BASIC ENERGY PARAMETERS**
- C/N Ratio > 100 $\rightarrow$ Lower Heating Value $f$ (C%): 4.1-4.2 kWh/kg DM
- MC = 15-25% $\rightarrow$ Net Heating Value $f$ (1/MC): 3.5-4.0 kWh/kg DM
- Ash (2-5% DM), frequently low melting (T < 1000 °C)

**Combustion**

**Alcoholic fermentation**

**Type D2**

*ON REPORT TABLES SPECIFIC PARAMETERS ARE INDICATED*
### Biomass-to-energy: some basic information

<table>
<thead>
<tr>
<th>TYPE</th>
<th>C/N</th>
<th>MOISTURE CONTENT</th>
<th>CONVERSION PROCESS</th>
<th>ENERGY PRODUCTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermochemical (heat)</td>
<td>&gt; 30</td>
<td>&lt; 40%</td>
<td>Combustion, Gasification, Pyrolysis</td>
<td>Heat → Electricity, Syngas, Syngas, Tar, Char</td>
</tr>
<tr>
<td>Biochemical (bacteria)</td>
<td>&lt; 30</td>
<td>&gt; 70%</td>
<td>Anaerobic Digestion, Alcoholic Fermentation</td>
<td>Biogas, BioCH₄, BioH, Bioethanol</td>
</tr>
<tr>
<td>Other (physical, chemical)</td>
<td>-</td>
<td>-</td>
<td>Extraction, Esterification</td>
<td>Straight Vegetable Oil (SVO), Biodiesel</td>
</tr>
</tbody>
</table>

- **Wood, straw, «dry» residues/waste**
- **Animal waste, «wet» residues, energy crops**
- **Seeds**
BIOMASS and BIOFULS – Part 2

Biomass-to-energy processes and plants

Prof. Marco Fiala

Department of Agricultural and Environmental Sciences. Production, Landscape, Agroenergy (DiSAA)

☎️ +39 02 503 16868  📧 marco.fiala@unimi.it

Università degli Studi di Milano
http://www.unimi.it/

http://www.disaa.unimi.it/
COMBUSTION $\rightarrow$ Heat $\rightarrow$ Mechanical energy $\rightarrow$ Electricity

Thermochemical process $\rightarrow$ ligno-cellulosic biomass (Type A)
COMBUSTION

Sequence of chemical reactions for which - in the presence of heat (starter) – a biomass (fuel) combines with the oxygen (of the air) developing Thermal Energy (ET). From chemical point of view, Exothermic oxide reduction in which some elements (mainly C, contained in cellulose, hemicellulose and lignin) oxidize while another (O) reduces, with release of energy and formation of carbon dioxide (CO₂) and water (H₂O as vapour).

The process is divided into three phases that occur in thermal devices at the same time: Drying: water loss from biomass → Gasification: very fast emission of a volatile fraction (gases) and final formation of a solid fraction (char) → Oxidation of the gasification products, gases (flame formation) and char (without flame).
BIOMASS

COMBUSTION

SMOKE
ASH

EE_L, EE_A, EE_N = Gross, Self-consumed, Net Electrical Energy
ET_L, ET_A, ET_N = Gross, Self-consumed, Net Thermal Energy

Type A

Wood, SRF, forestry residues
Agricultural by-products
Agro-industries residues
Cereals grain

PROCESS

ENERGY PRODUCTS

OUTLET

ENERGY FINAL DESTINATION

EXTERNAL USERS (DOMESTIC, PRODUCTIVE)

ELECTRICAL GRID

POWER CYCLE ET → EM → (EE+ET)
WOOD LOGS (coppice)
**Wood logs heat generators (PT = 10-50 kW)**

### BASIC TECHNICAL CHARACTERISTICS

- **BIOMASS LOAD:** manual. **GRATE:** yes (flat).
- **AIR SUPPLY:** 1st and 2nd fluxes, adjustable, natural draft or fan. **ASH REMOVAL:** manual. **HEAT STORAGE:** recomended (puffer; 800-1000 lt). **COMBUSTION TYPE:** rising or reverse.
- **THERMAL EFFICIENCY:** 60-65% or 85-95% (rising or reverse combustion, respectively). **ENERGY USE:** heat home requirements. **THERMAL FLUID:** water. **PLANT INTEGRATION:** possible (solar collectors).
CHIPPED WOOD (coppice/tall trees, SRC, wood residues)
**WOOD CHIPS**

**BIOMASS LOAD:** mechanical (screw). **GRATE:** no. **AIR SUPPLY:** 1st and 2nd fluxes, adjustable, fan. **ASH REMOVAL:** manual or mechanical. **HEAT STORAGE:** recommended (puffer; 1000-2000 lt). **COMBUSTION TYPE:** rising. **THERMAL EFFICIENCY:** 75-85%. **ENERGY USE:** heat home requirements. **THERMAL FLUID:** water. **PLANT INTEGRATION:** possible (solar collectors).

250-350 kg/m³
MC = 25-40%
Wood chips heat generators (PT = 1-20 MW) → ET, EE

**WOOD CHIPS**

**BIO MASS LOAD**: mechanical (screw, hydraulic piston). **GRATE**: yes (fix or inclined and mobile). **AIR SUPPLY**: 1<sup>st</sup> and 2<sup>nd</sup> fluxes, adjustable, fans. **ASH REMOVAL**: mechanical (screw). **HEAT STORAGE**: yes. **COMBUSTION TYPE**: rising. **THERMAL EFFICIENCY**: 75-85%. **ENERGY USE**: industrial requirements, heating districts, electricity/heat generation. **THERMAL FLUID**: water (T = 90-95 °C), steam, diathermic oil. **PLANT INTEGRATION**: no.

**RANKINE CYCLE → Electricity**

- Wood chips 250-350 kg/m³ MC = 25-40%
PELLET
BASIC TECHNICAL CHARACTERISTICS

BIOMASS LOAD: semi-manual (bags) or mechanical (screw + hopper). 

GRATE: no. 

AIR SUPPLY: 1st and 2nd fluxes, adjustable, fan. 

ASH REMOVAL: manual. 

HEAT STORAGE: recommended (puffer; 800-1000 lt). 

COMBUSTION TYPE: rising. 

THERMAL EFFICIENCY: 75-85%. 

ENERGY USE: heat home requirements. 

THERMAL FLUID: water. 

PLANT INTEGRATION: possible (solar collectors).
CORN GRAIN
**BASIC TECHNICAL CHARACTERISTICS**

**BIOMASS LOAD:** mechanical (hopper + screw).  
**GRATE:** no.  
**AIR SUPPLY:** 1\textsuperscript{st} and 2\textsuperscript{nd} fluxes, adjustable, fan.  
**ASH REMOVAL:** manual.  
**HEAT STORAGE:** recommended (puffer; 800-1000 lt).  
**COMBUSTION TYPE:** rising.  
**THERMAL EFFICIENCY:** 75-85\%.  
**ENERGY USE:** heat home requirements.  
**THERMAL FLUID:** water.  
**PLANT INTEGRATION:** possible (solar collectors).  
**OPERATING PROBLEMS:** low melting ash, Cl \geq 1\% (corrosion); high level particulate (PM\textsubscript{10}).
AGRINCULTURAL BY-PRODUCTS → STRAW
Cereal straw heat generators (PT = 15-30 kW) → ET (PT = 10-20 MW) → EE

**CEREALS BALED STRAW**

**BIO MASS LOAD:** manual (lp), mechanical (hp). **GRATE:** no/yes (lp). Yes (hp), Flat or mobile. **AIR SUPPLY:** 1\textsuperscript{st} and 2\textsuperscript{nd} fluxes, adjustable, natural draft (lp) or fan (hp). **ASH REMOVAL:** manual (lp), mechanical (hp). **HEAT STORAGE:** yes. **COMBUSTION TYPE:** rising **THERMAL EFFICIENCY:** 50-55\% (lp), 75-80\% (hp). **ENERGY USE:** heat home requirements (lp), electricity/heat (hp). **THERMAL FLUID:** water (lp), steam (hp). **PLANT INTEGRATION:** no.

**LOWPOWER (lp)**

**MEDIUM POWER**

**HIGH POWER (hp)**
Residues & waste processing industries heat generators (PT = 20-50 kW) → ET; (PT = 1-5 MW) → ET, EE

**INDUSTRIAL RESIDUES**

- **Biomass Load**: mechanical (hopper + screw)
- **Grate**: no
- **Air Supply**: 1st and 2nd fluxes, adjustable, fan
- **Ash Removal**: mechanical
- **Heat Storage**: yes
- **Combustion Type**: rising
- **Thermal Efficiency**: 75-85%
- **Energy Use**: processing heat; heating district
- **Thermal Fluid**: water, steam, diatermic oil
- **Plant Integration**: -
- **Operating Problems**: low melting ash, high level particulate (PM$_{10}$)

**BASIC TECHNICAL CHARACTERISTICS**

- **Biomass Load**: mechanical (hopper + screw)
- **Grate**: no
- **Air Supply**: 1st and 2nd fluxes, adjustable, fan
- **Ash Removal**: mechanical
- **Heat Storage**: yes
- **Combustion Type**: rising
- **Thermal Efficiency**: 75-85%
- **Energy Use**: processing heat; heating district
- **Thermal Fluid**: water, steam, diatermic oil
- **Plant Integration**: -
- **Operating Problems**: low melting ash, high level particulate (PM$_{10}$)

**LOWPOWER**

**HIGH POWER**

**SCREW FEEDER**

**MEDIUM POWER**
GASIFICATION $\rightarrow$ Gas $\rightarrow$ Mechanical energy $\rightarrow$ Electricity (Heat)

Thermochemical process $\rightarrow$ ligno-cellulosic biomass (Type A)
GASSIFICAZIONE

Incomplete oxidation of a substance in a high temperature environment (900÷1000 °C) for the production of a gas (gasogen gas or producer gas) with a low LHV = 1.1-1.2 kWh/m³. This gas is used – after a gas cleaning action - to supply I.C. engines, generating mechanical energy (EM) and, consequently, electricity (EE). Using a CHP unit the recovery heat (ET) can be used within the same process (eg: biomass drying) or for covering external requirements. Global efficiency (biomass-to-electricity) is 18-20%.

<table>
<thead>
<tr>
<th></th>
<th>AIR (g/kg DM)</th>
<th>OXIGEN (g/kg DM)</th>
<th>STEAM (g/kg DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>12-15</td>
<td>30-37</td>
<td>32-41</td>
</tr>
<tr>
<td>CO₂</td>
<td>14-17</td>
<td>25-29</td>
<td>17-19</td>
</tr>
<tr>
<td>H₂</td>
<td>9-10</td>
<td>30-34</td>
<td>24-26</td>
</tr>
<tr>
<td>CH₄</td>
<td>2-4</td>
<td>4-6</td>
<td>12,4</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>0,2-1</td>
<td>0,7</td>
<td>2,5</td>
</tr>
<tr>
<td>N₂</td>
<td>56-59</td>
<td>2-5</td>
<td>2,5</td>
</tr>
<tr>
<td>LHV (kWh/m³)</td>
<td>1,0-1,3</td>
<td>2,7-2,8</td>
<td>3,3-3,6</td>
</tr>
<tr>
<td>Yield (m³/kg DM)</td>
<td>2,3-3,0</td>
<td>1,3-1,5</td>
<td>-</td>
</tr>
</tbody>
</table>

η = 18-20%  ELECTRICITY  0.7-0.8 kWh
η = 40-45%  HEAT  1.6-1.8 kWh
The **gas composition** varies depending on the characteristics of the biomass (**moisture content**) and the operating parameters (**temperature**) as well as the **oxidizing agent**.
Gasification:

- Wood, SRF, forestry residues
- Agricultural by-products
- Agro-industries residues

Gasification:

- GASIFICATION
- ASH
- FLUE-GAS
- H₂O GAS CLEANING

Energy Products:

- EEₙ
- EEₐ
- EEₗ

Energy Final Destination:

- ELECTRICAL GRID

External Users (Domestic, Productive):

- EXTERNAL USERS (DOMESTIC, PRODUCTTIVE)

Marco Fiala (UniMI - DiSAA)

EEₗ, EEₐ, EEₙ = Gross, Self-consumed, Net Electrical Energy
ETₗ, ETₐ, ETₙ = Gross, Self-consumed, Net Thermal Energy
FIXED BED GASIFIERS
Up-draft and down-draft gasifiers

- **Biomass**
- **Air**
- **Ash**

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>150-300 °C</td>
<td>Drying</td>
</tr>
<tr>
<td>600-800 °C</td>
<td>Pyrolysis VS prod. (tar)</td>
</tr>
<tr>
<td>1000-1200 °C</td>
<td>Oxidation (charcoal)</td>
</tr>
</tbody>
</table>

- **GAS**
PYROLYSIS $\rightarrow$ Syngas, tar, char $\rightarrow$ Mechanical Energy $\rightarrow$ Electricity (Heat)

Thermochemical process $\rightarrow$ Ligno-cellulosic biomass (Type A)
PYROLYSIS

Thermal degradation in the absence of oxidants that occurs by providing medium-temperature heat (400÷800 °C) indirectly through the reactor walls, or directly by shaking a heating medium in the biomass bed and leading to the production of:

- non-condensable gases (syngas) which can be (i) burnt to provide heat to the pyrolysis reactor (ii) used as fuel I.C. engines, producing electricity (EE).
- condensable volatile compounds (tar or bio-oil), complex and variable composition liquid (heavy hydrocarbons)
- solid (char) compounds consisting of carbonaceous residues (similar to wood charcoal) and ashes. Char can be used as a fuel for the production of activated carbon or as intermediate in the chemical industry.
Pyrolysis: scheme

**PROCESS**

**OUTLET**

**ENERGY PRODUCTS**

**ENERGY FINAL DESTINATION**

**Biomass**

**Outlet**

**Energy Products**

**Energy Final Destination**

**Pyrolysis**

**Type A**

- Wood, SRF, forestry residues
- Agricultural by-products
- Agro-industries residues

**Flue-gas**

**Smoke**

**Ash**

**Char**

**TAR**

**Syngas**

**CHP**

**EE_N**

**EE_A**

**EE_L**

**Electric Grid**

**Raw Material**

**EE_L, EE_A, EE_N = Gross, Self-consumed, Net Electrical Energy**

**ET_L, ET_A, ET_N = Gross, Self-consumed, Net Thermal Energy**
Type of pyrolysis processes

- **Flash**: $> 10^6 \text{ W/m}^2$
- **Fast**: $> 10^5 \text{ W/m}^2$
- **Medium**: $> 10^4 \text{ W/m}^2$
- **Slow**: $> 10^3 \text{ W/m}^2$

**Temperature (°C)**: 1000, 500

**Retention Time (s)**: $10^{-2}$, 1, $10^2$, $10^4$

- **Syngas**
- **Tar**
- **Char**

**Carbonization**: Charcoal production
ANAEROBIC DIGESTION ➔ Biogas ➔ Mechanical energy ➔ Electricity (Heat)

Biochemical process ➔ Fermentable biomass (Type B and C)
ANAEROBIC DIGESTION (AD)

Biological process (bacterial consortium) by which the organic matter (plant or animal origin), in the absence of oxygen (anerobiosis), is degraded by the formation of a gas mixture (biogas), and a co-product (digestate) used as fertilizer.

<table>
<thead>
<tr>
<th>COMPOUND</th>
<th>% vol-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH₄)</td>
<td>50 – 65%</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>30 – 50%</td>
</tr>
<tr>
<td>Water (H₂O)</td>
<td>10%</td>
</tr>
<tr>
<td>Hydrogen sulfide (H₂S)</td>
<td>2%</td>
</tr>
<tr>
<td>Siloxanes</td>
<td>0,02%</td>
</tr>
<tr>
<td>Halogenated hydrocarbons (VOC)</td>
<td>&lt; 0,6%</td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>1%</td>
</tr>
<tr>
<td>Carbon monooxide (CO)</td>
<td>&lt; 0,6%</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>2%</td>
</tr>
</tbody>
</table>

CH₄ LHV 9,9 kWh/m³_N = 8575 kcal/m³_N
1 m³_N of biogas ≅ 0,5-0,6 dm³ oil

DEHUMIDIFICATION and DESULPHURIZATION

UPGRADING

HEAT

ELECTRICITY + HEAT

BIO-METHANE

FERTILIZER

Methanic fermentation (Anaerobic Digestion): the process
Microbiological process scheme

- **PROTEINS**
- **CARBOHYDRATES**
- **FATS**

**PROCESS**
- Hydrolysis
- Fermentation (acidogenesis)
- Fermentation (acetogenesis)
- Methanogenesis

**BACTERIA**
- Hydrolitic
- Acidogenic
- Acetogenic
- Methanogens

**AMINO ACIDS, SUGARS, ORGANIC ACIDS**

**VOLATILE FATTY ACIDS**

**ACETIC ACID, HYDROGEN...**

**CH₄ e CO₂**

Marco Fiala (UniMI - DiSAA)
Co-digestion process

ENERGY CROPS

DIGESTOR(s)

DIGESTATE (N-P-K)

TREATMENTS

BIOGAS

MIXER/FEEDER

ANIMAL WASTE

AGRO-INDUST. RESID., OFMSW

STORAGE

STORAGE

STORAGE

CHP

H₂O 85°C

EE

ET

GRID

THERMAL FINAL USERS

MARCO FIALA (UNIMI - DISAA)

ENERGY CROPS

DIGESTOR(s)

DIGESTATE (N-P-K)

TREATMENTS

BIOGAS

MIXER/FEEDER

ANIMAL WASTE

AGRO-INDUST. RESID., OFMSW

STORAGE

STORAGE

STORAGE

CHP

H₂O 85°C

EE

ET

GRID

THERMAL FINAL USERS

MARCO FIALA (UNIMI - DISAA)
Plant types (from left to right and from top to bottom):
(1) single-stage plant, mechanical mixing; (2) two-stage plant, mechanical mixing;
(3) continuous load system; (4) discontinuous load system (batch);
(5) not mixed plant; (6) mixed plant (Completely Stirred Tank Reactor, CSTR); (7) plug-flow plant.
Biogas plant (co-digestion); two digesters

- Biogas storage
- Digestate storage and treatment
- Biogas treatments Co-generation unit (CHP)
- Feeding system (solid biomass)
ANAEROBIC DIGESTION $\rightarrow$ BioCH$_4$, BioH

Biochemical process $\rightarrow$ Fermentable biomass (Type B and C)
Bio-methane (bio\(CH_4\)) scheme

**BIOGAS**

- **BIOGAS**
- **BIOGAS**
- **BIOGAS**

**BIOGAS**

- **BIOGAS**
- **BIOGAS**

**BIOGAS**

- **BIOGAS**
- **BIOGAS**

**UPGRADING**

- **UPGRADING**
- **UPGRADING**

**BIOMETHANE**

- **BIOMETHANE**
- **BIOMETHANE**

**BIOMETHANE**

- **BIOMETHANE**
- **BIOMETHANE**

**BIOMETHANE**

- **BIOMETHANE**
- **BIOMETHANE**

**RURAL AREAS**

- **URBAN AREAS**

**FUEL**

- (heating)
- (vehicles)

**THERMAL USERS**

- (domestic, industrial)

**CHP**

- (high power)

**DISTRICT HEATING**

**GRID**

**EE**

**ET**

Marco Fiala (UniMI - DiSAA)
**PHASE 1**
**HYDROLYSIS and ACIDOGENIC**

**PHASE 2**
**METHANOGENIC**

**BIOHYDROGEN**

**BIOGAS**

**BIOGAS**

**DIGESTATE**

**FATTY VOLATILE ACIDS**

**1st DIGESTER**

**2nd DIGESTER**

**Biomass**

**CO₂**

**H₂**

**CH₄**

**BioHydrogen (bioH) + Fuel Cell: scheme**

**Fuel Cell Stack**

Key:
- **Red** Hydrogen
- **Blue** Protons (+ve)
- **Orange** Oxygen
- **Yellow** Electron (-ve)

**H₂ Recycling**

**Gas Diffusion Layer**

**Catalyst**

**Proton Exchange Membrane**

**Gas Diffusion Layer**

**Anode**

**Cathode**

**Oxygen O₂ From Air**

**Air and Water Vapour**

**H₂ Fuel**

**Battery Pack**
ALCHOLIC FERMENTATION ➔ BioEthanol

Biochemical process ➔ biomass for sugar, starch (Type D)
Colture zuccherine
Residui zuccherini
Colture amidacee

BIOMASSA

PRETRATTAMENTO
PRETRATTAMENTO e IDROLISI
FERMENTAZIONE
DISTILLAZIONE
BIOETANOLO
DDGS

PROCESSO

PRODOTTO ENERGETICO

MISCELAZIONE

ETBE

DESTINAZIONE ENERGIA

MISCELAZIONE

AUTOTRAZIONE

1st generation:
scheme

Marco Fiala (UniMI - DiSAA)
Bio-ethanol 2nd generation: scheme

Colture lignocellulosica
Residui lignocellulosici

BIOMASSA

PROCESO

PRODOTTO ENERGETICO

DESTINAZIONE ENERGIA

EFFlUENTE

PRETRATTAMENTO

DETROSSIFICAZIONE

NEUTRALIZZAZIONE

LIGNINA

IDROLISI

FERMENTAZIONE

DISTILLAZIONE

DDGS

BIOETANOLO

ETBE

MISCELAZIONE

AUTOTRAZIONE
OIL EXTRACTION ➔ SVO, BioDiesel

Mechanical/chemical process ➔ Oil crop seeds (Type D)
Colture oleaginose climi temperati (Girasole, Colza)

Colture oleaginose tropicali (Jatropha, Palma da olio)

Grassi Animali

BIOMASSA

PROCESSO

PRODOTTO ENERGETICO

DESTINAZIONE ENERGIA

EE_L

EE_1

RETEN

BIODIESEL

EM

ET_L

OLIO VEGETALE PURO

TRANSESTERIFICAZIONE

ESTRAZIONE RAFFINAZIONE

PANELLO FARINA

GLICEROLO

FUMI

AUTOTRAZIONE

DISIPAZIONE

AUTOCONSUMO

UTENZE ESTERNE CIVILI O PRODUTTIVE

TRAZIONE (trattori)

SVO e bio-Diesel: scheme

Marco Fiala (UniMI - DiSAA)
Biomass
EVERYTHING IS POSSIBLE!
Well ... almost everything!

Prof. Marco Fiala  ++39 02 503 16868  marco.fiala@unimi.it
Department of Agricultural and Environmental Sciences. Production, Landscape, Agroenergy