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Course on Biomass-to-Energy Technologies

Torrefaction of biomass

by

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Limitations of biomass as fuel

Compared to fossil fuel resources:

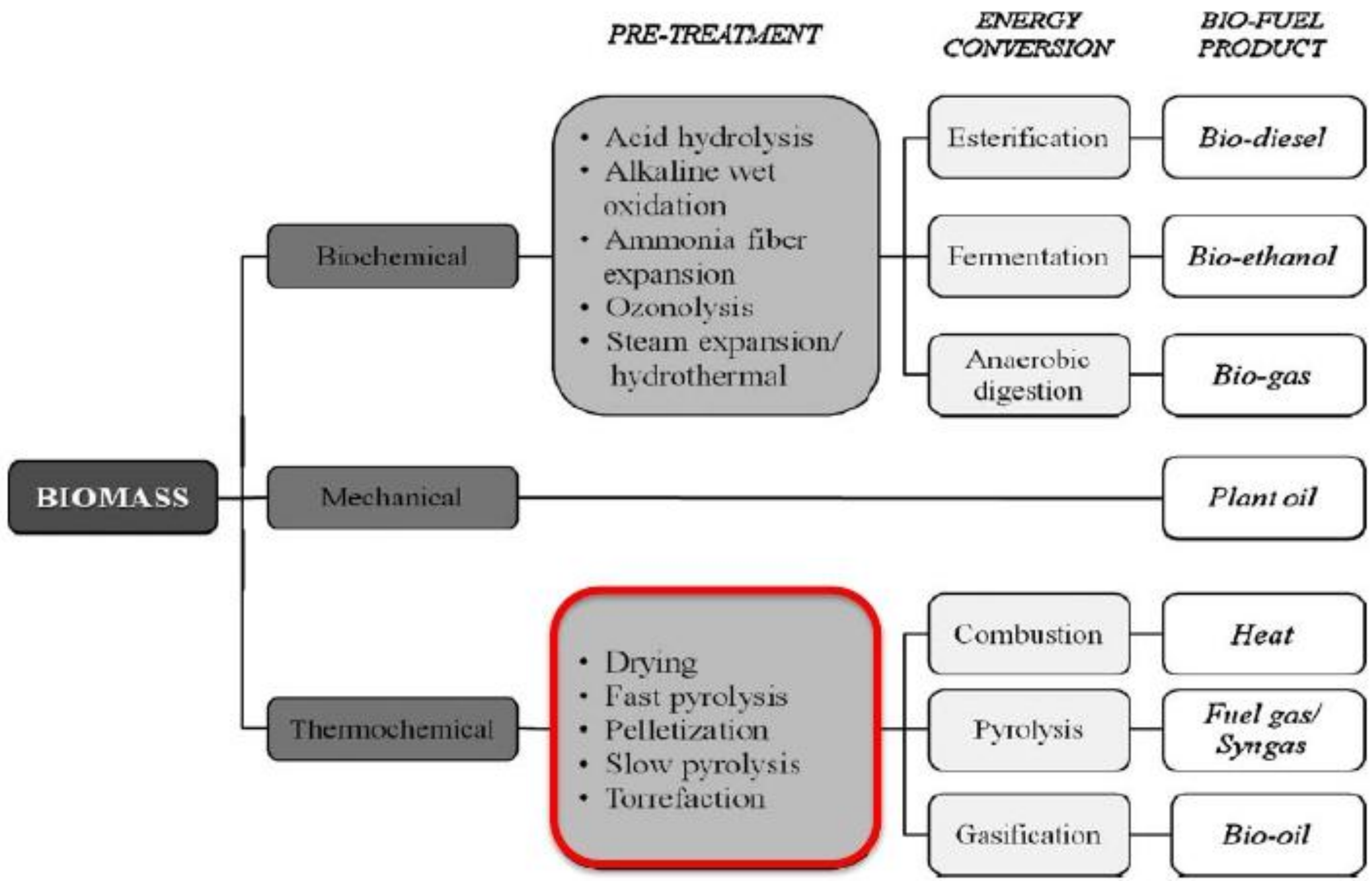
- low bulk density,
- high moisture content,
- hydrophilic nature,
- low calorific value

Consequences:

- Raw biomass difficult to use on a large scale
- High volumes of biomass are needed
  - *Problems associated with storage, transportation, and feed handling, …*
- Impact logistics and final energy efficiency

Limitations of biomass as fuel

Considered collectively, these properties make raw biomass unacceptable for energy applications: the material must be Preprocessed.

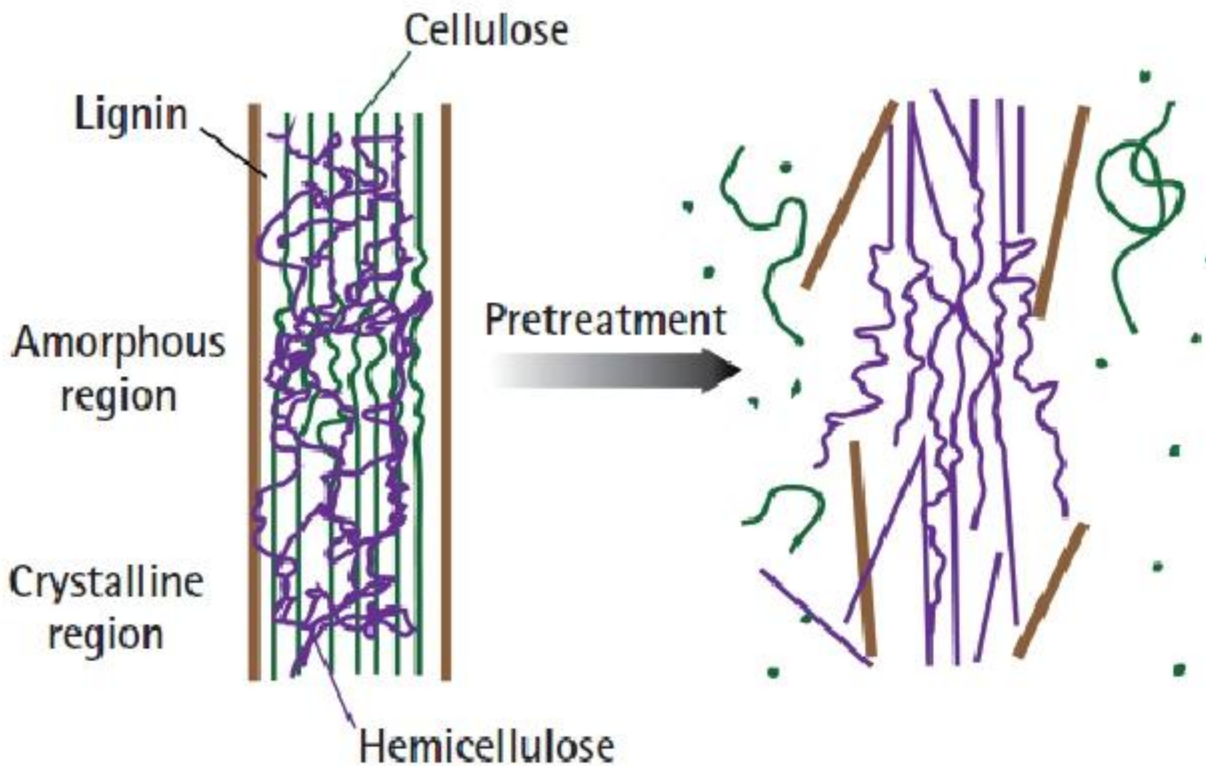


Summary of biofuel conversion routes

J.J. Chew, (2011) :

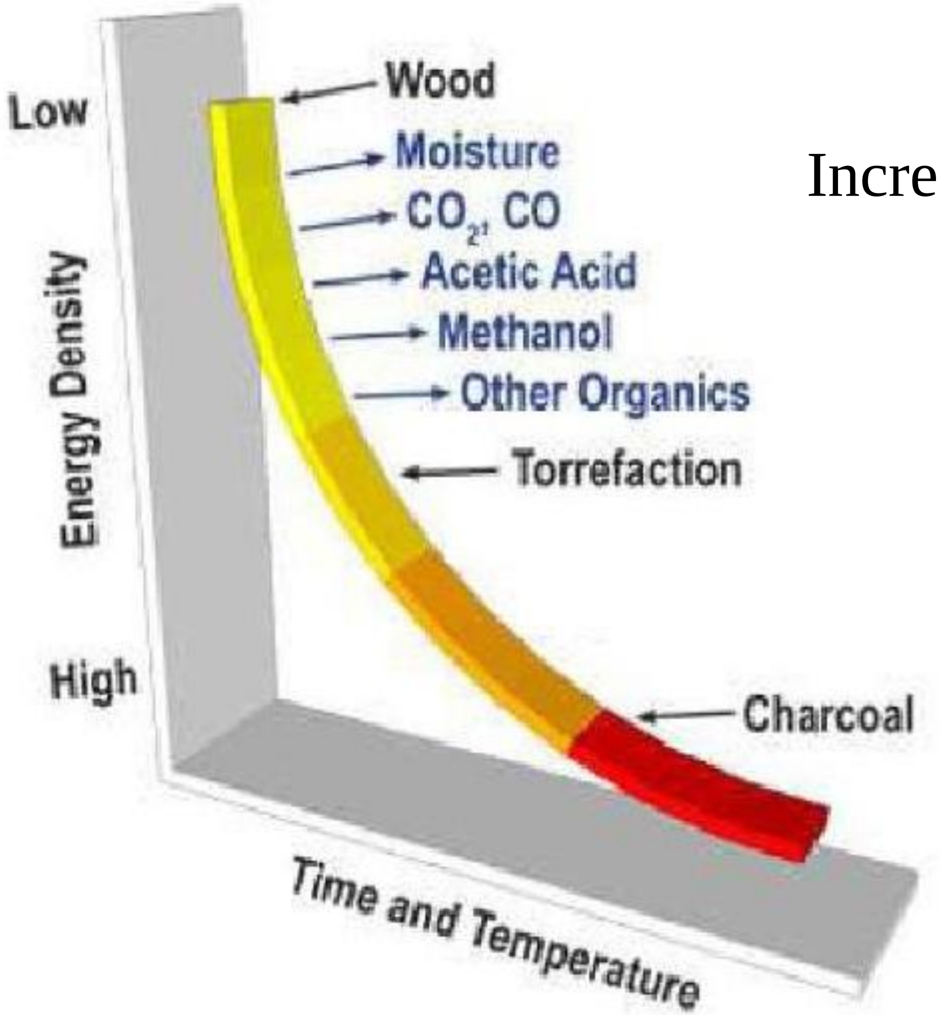
Limitations of biomass as fuel

Pre-treatment alters of the amorphous and crystalline regions of the biomass and bring significant changes in structural and chemical compositions.



Pretreatment effect on lignocellulosic biomass, (Tumuluru, 2011)

Limitations of biomass as fuel

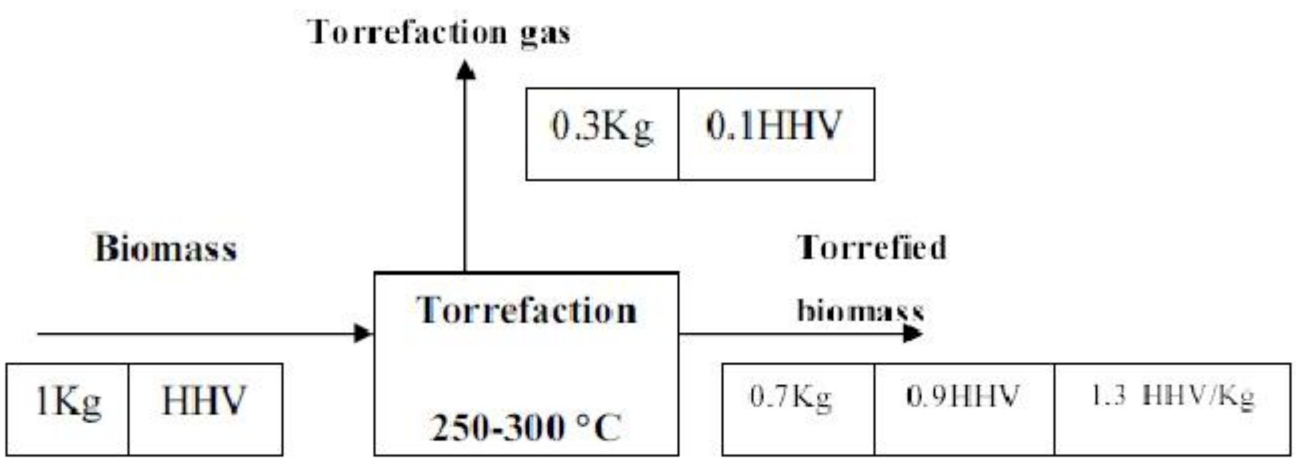


Thermochemical preprocessing operations

Increase energy density

Torrefaction as a pre-treatment

- **Torrefaction** is a thermal pretreatment process defined as slowly heating biomass in an inert environment and temperature range of 200–300° C.
- During the process, the biomass partly decomposes giving off various condensable and non-condensable gases. The final product is a carbon rich solid, which is referred to as torrefied biomass.
- Several names, such as roasting, slow and mild pyrolysis, wood-cooking and high-temperature drying.



Typical mass and energy balance of the torrefaction process

Torrefaction as a pre-treatment

The principal characteristics of torrefied products are as follows (1):

- 1. High Energy Density:
  - Torrefied biomass contains 70-80% of the original weight while retaining 80-90% of original energy of the biomass. In effect, there can be an increase of around 30% in its energy density.
- 2. Hydrophobicity:
  - Torrefied biomass becomes hydrophobic, i.e., it does not absorb moisture or its equilibrium moisture percentage drops. The equilibrium moisture content of torrefied biomass is very low (from 1 to 3%)
- 3. Increased Fixed Carbon:
  - The fixed carbon content of torrefied biomass is high. For example, depending on the treatment temperature and duration, it is between 25% and 40%, while the ash content is low. This property makes the torrefied wood a very attractive reducing agent.

Torrefaction as a pre-treatment

The principal characteristics of torrefied products are as follows (2):

- 4. Reduced Oxygen:
  - Torrefaction reduces the O/C ratio through reduction in oxygen. This makes a biomass better suited for gasification due to its lower O/C ratio.
- 5. Improved Grindability:
  - Torrefied biomass grindability is superior to that of raw biomass. the energy requirements for grinding reduces dramatically when biomass is first torrefied from 70–90%,
- 6. Combustion Properties:
  - Torrefied biomass takes less time for ignition due to less moisture and it burns longer due to larger percentage of fixed carbon compared to raw biomass

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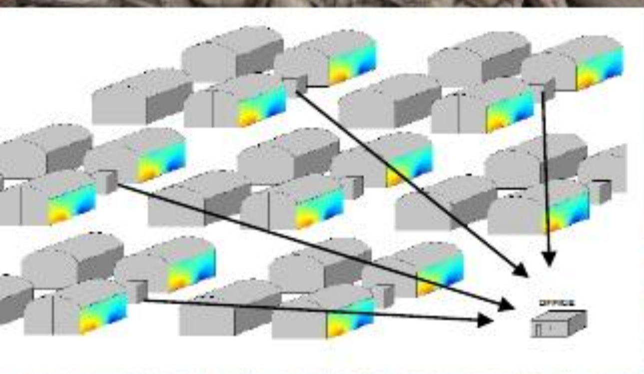

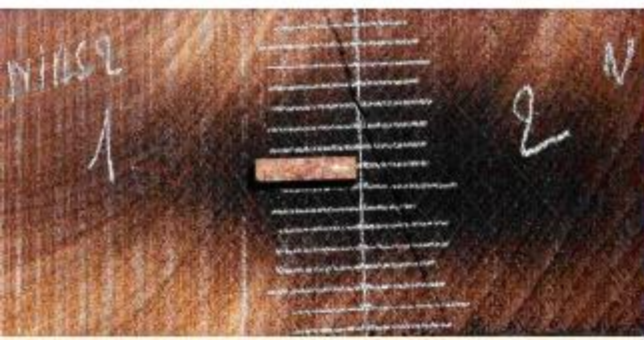

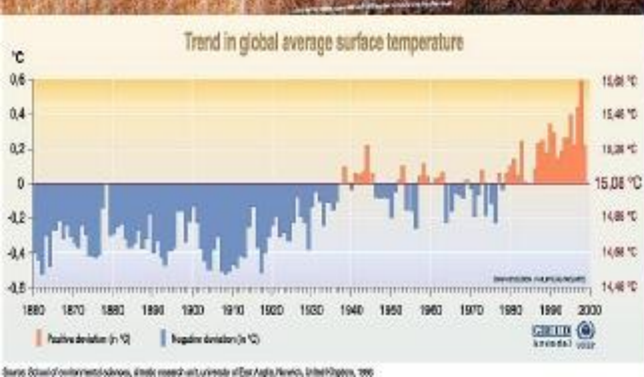

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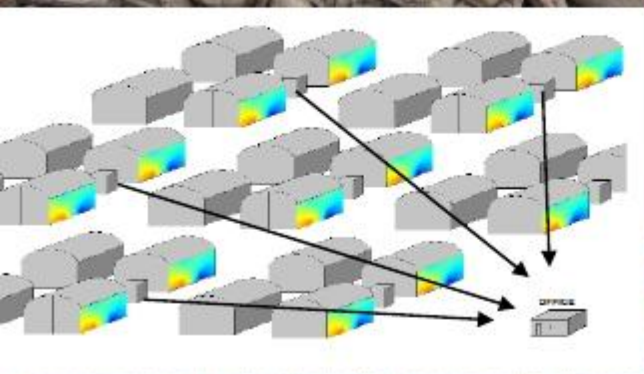
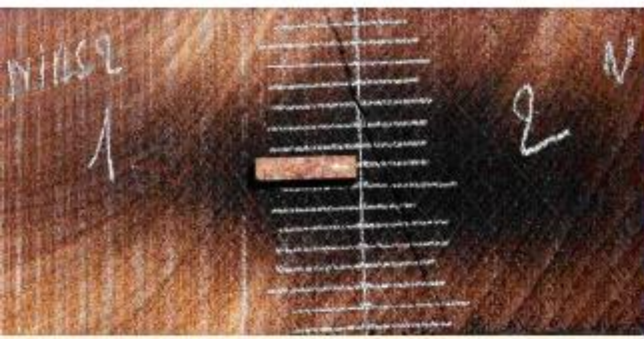
II - Torrefaction product yields in terms of condensable, non-condensable, and solid product

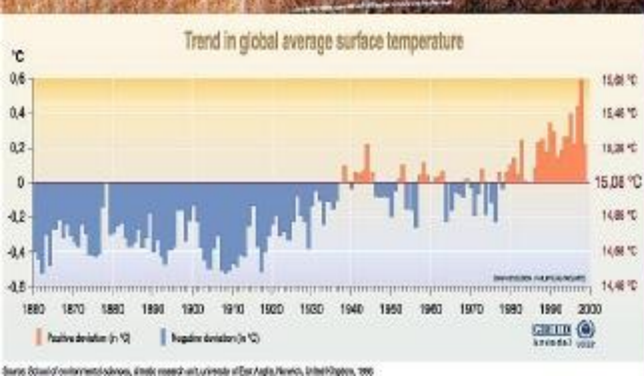
III - Solid torrefied product’s physical, chemical

IV – Models

V - Technologies







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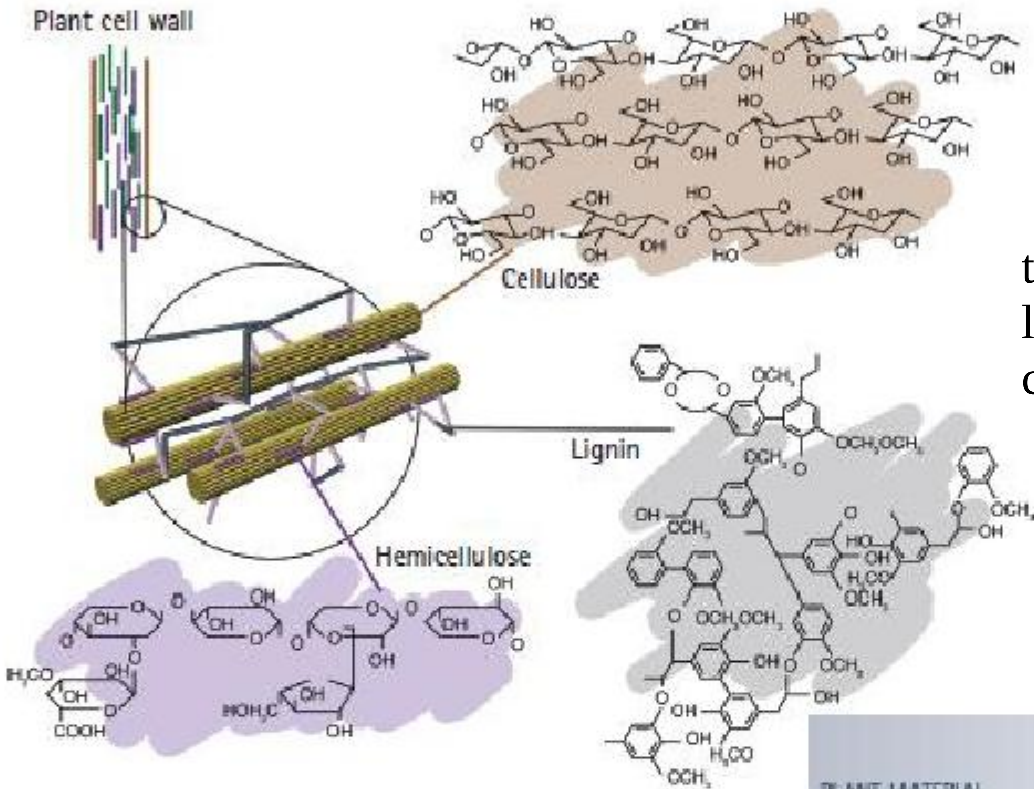
I - Biomass reactions, including chemical and structural changes



the plant cell wall and lignocellulosic biomass composition

typical lignocellulosic content of some plant

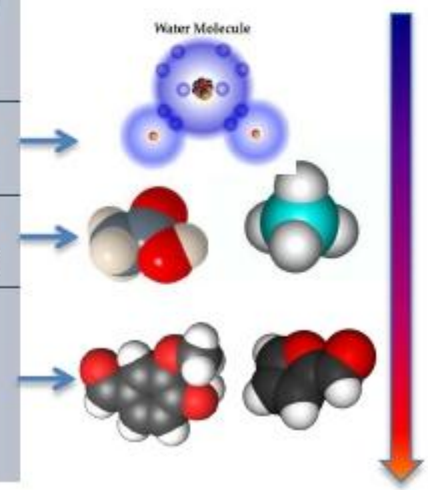
PLANT MATERIAL	LIGNOCELLULOSIC CONTENT (%)		
	HEMICELLULOSE	CELLULOSE	LIGNIN
Orchard grass (medium maturity)	40.0	32.0	4.7
Rice straw	27.2	34.0	14.2
Birch wood	25.7	40.0	15.7
Reed canary grass	29.7	42.6	7.6
Wheat straw	30.8	41.3	7.7
Willow	14.1	49.3	20.0

I - Biomass reactions, including chemical and structural changes

Thermal treatment process variables for different temperature regimes : mass and energy yields

\- Molecular weight

TEMPERATURE (°C)	TIME (min)	PROCESS REACTIONS	HEATING RATE (°C/min)	DRYING ENVIRONMENT AND PRESSURE	MASS YIELD (%)	ENERGY YIELD (%)
50–150	30–120	Nonreactive drying (moisture removal and structural changes)	<50	Air and ambient pressure	~90–95	Not significant
150–200	30–120	Reactive drying (moisture removal and structural damage due to cell wall collapse)	<50	Air and ambient pressure	~90	Needs to be researched
200–300	<30	Destructive drying ➤ Devolatilization and carbonization of hemicellulose ➤ Depolymerization and devolatilization/softening of lignin ➤ Depolymerization and devolatilization of cellulose	<50	Inert environment and ambient pressure	~70	~90



\+ molecular weight

$$\text{Mass Yield(daf)} = \frac{\text{Mass(daf) of torrefied biomass}}{\text{Mass(daf) of raw biomass}}$$

$$\text{Energy yield (daf)} = \frac{\text{Mass (daf) of torrefaction product x Heating value of torrefied product}}{\text{Mass (daf) of raw biomass x Heating value of raw biomass}}$$

The energy yield reflects the magnitude of energy conversion of the biomass during the torrefaction process. This will be beneficial for a reasonable assessment of the pretreatment process.

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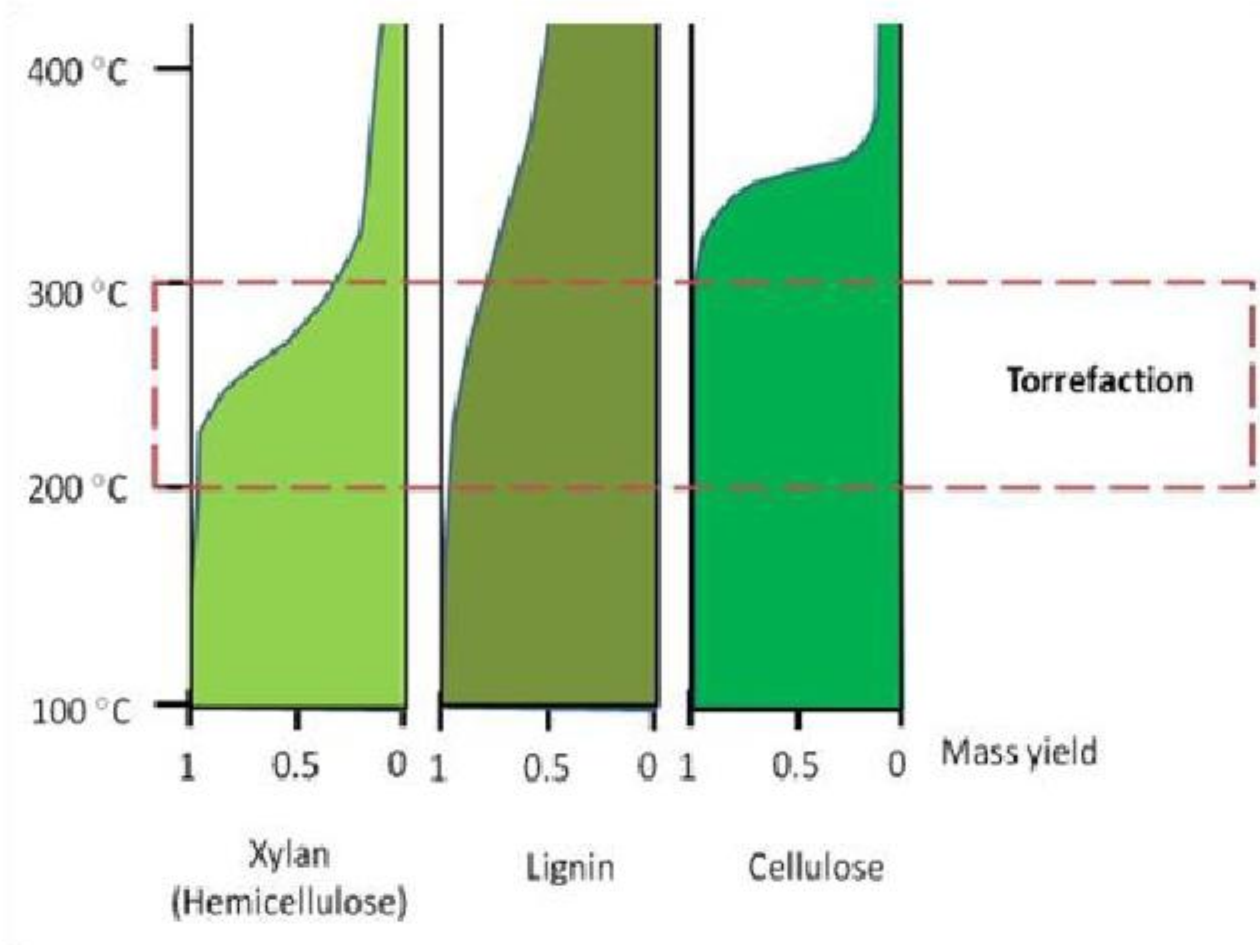
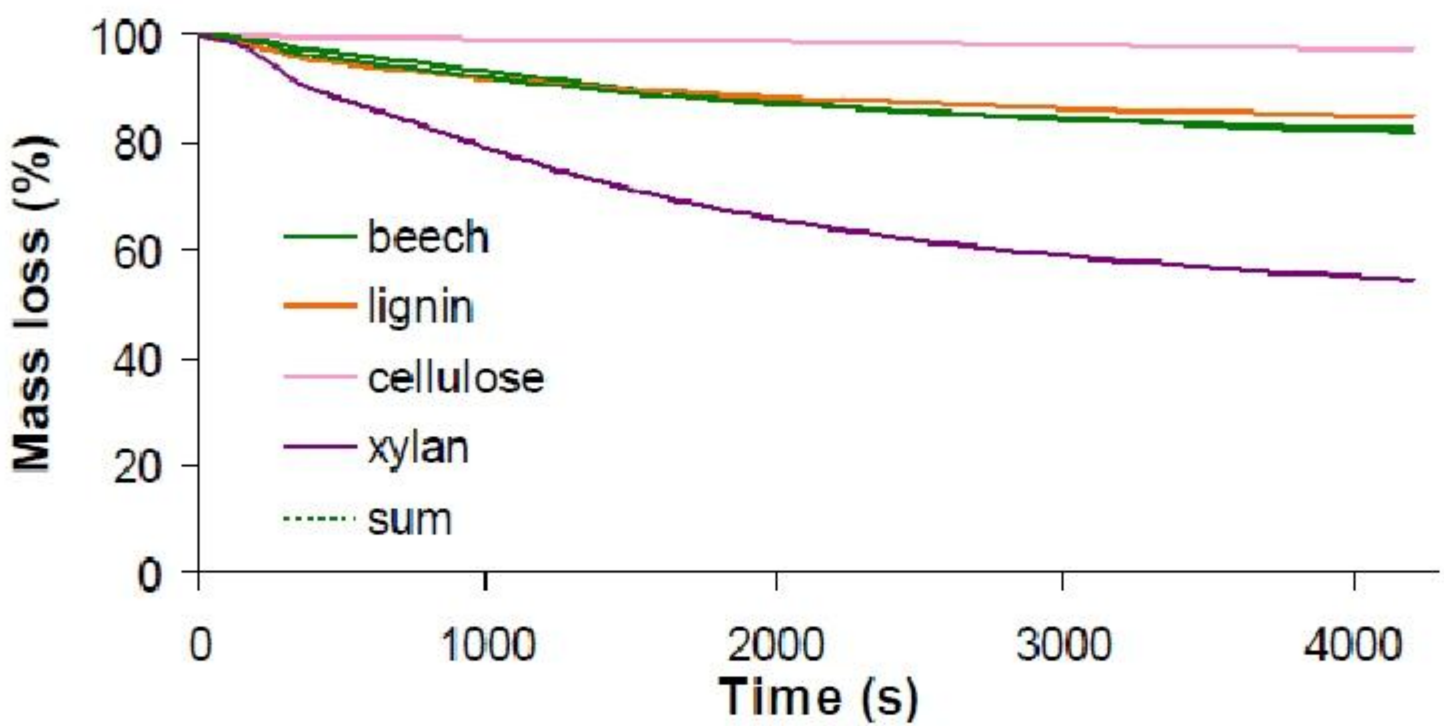
I - Biomass reactions, including chemical and structural changes



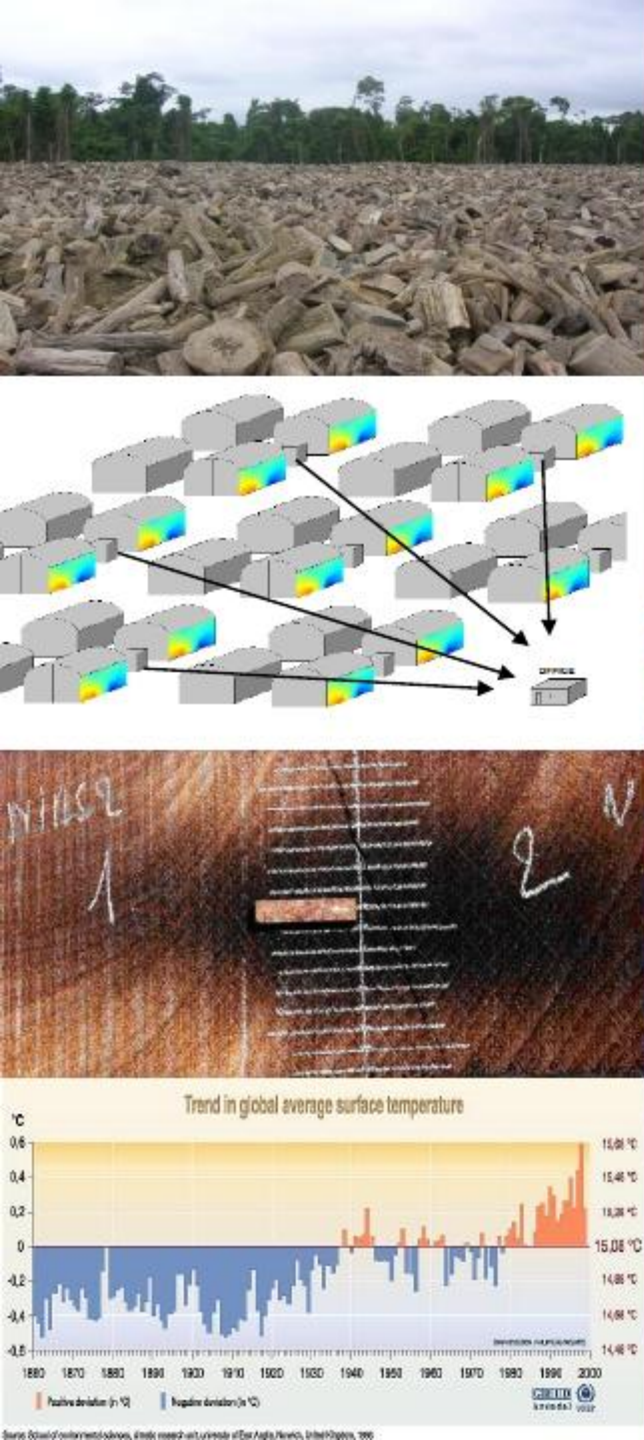
Relative thermal decomposition of the lignocellulose components (Dhungana, 2011)

I - Biomass reactions, including chemical and structural changes



- Lignin: smooth and continuous mass loss
- Xylan: significant mass loss
- Cellulose: nearly no mass loss
- Additive law: OK

(Nocquet et al. 2010)



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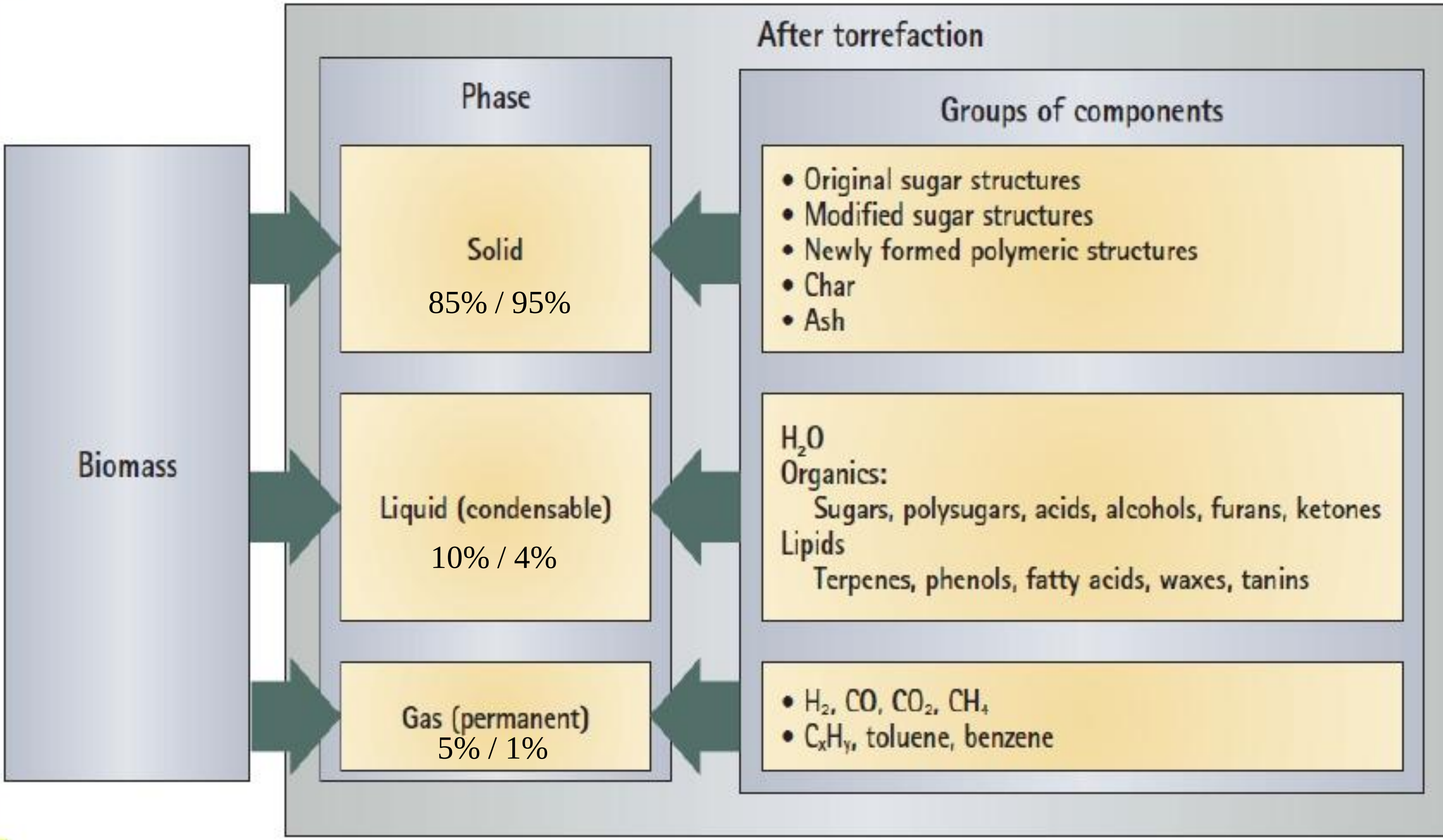
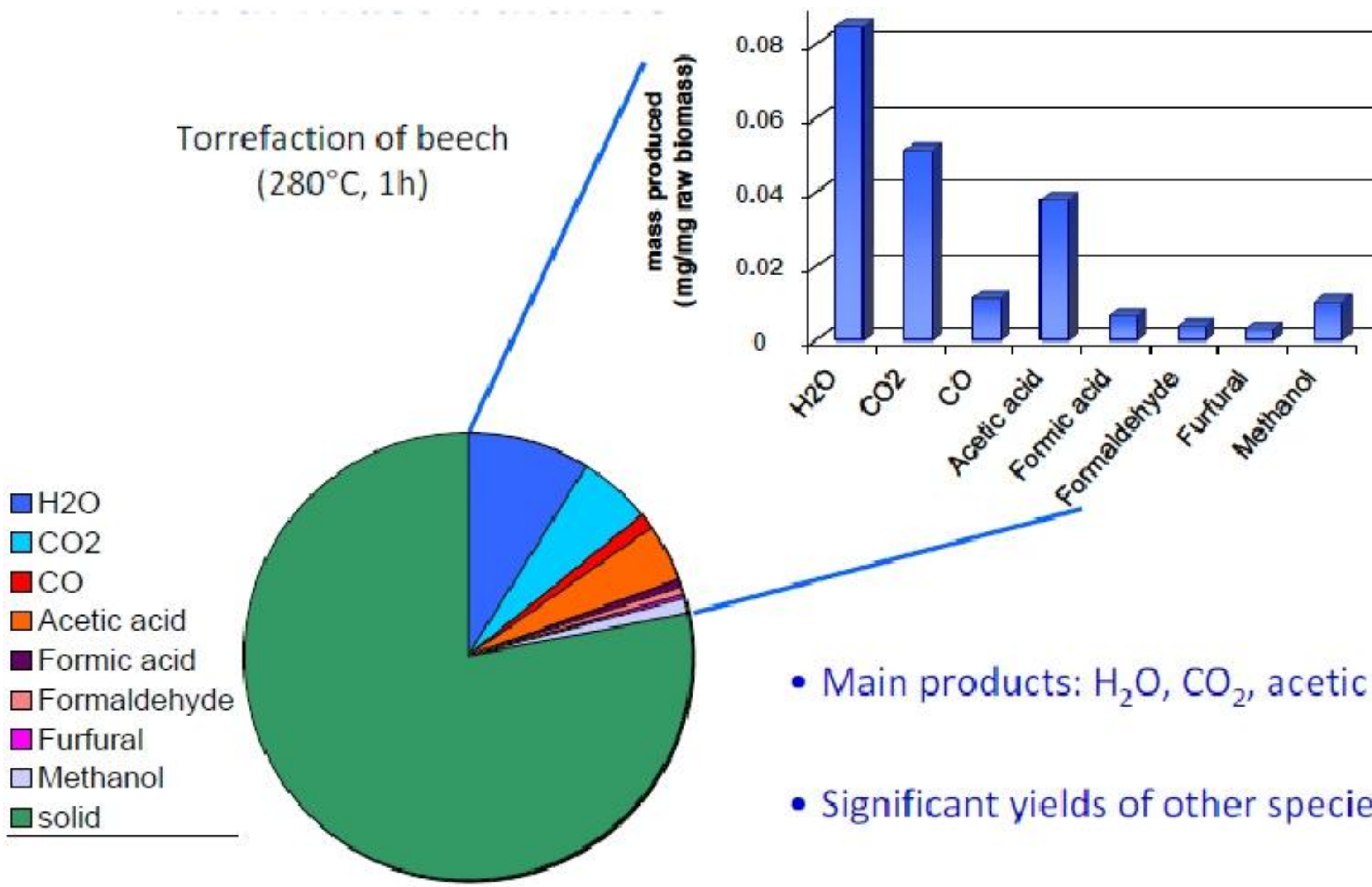


Products formed during torrefaction of biomass:
Average values : Mass yield (%)/Energy yield (%)

II - Torrefaction product yields in terms of condensable, non-condensable, and solid product



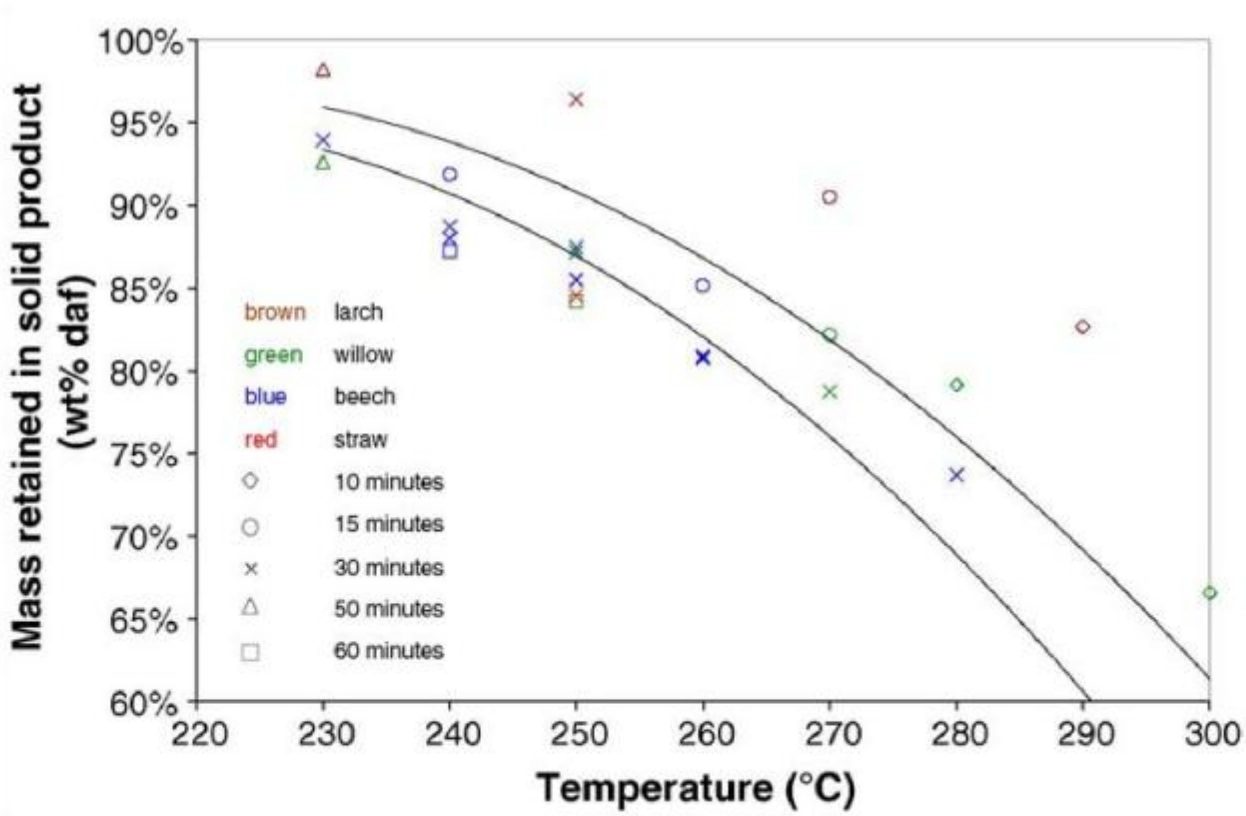
- Main products: H_2O, CO_2, acetic acid
- Significant yields of other species

Products formed during torrefaction of biomass

(Nocquet, 2010)

II - Torrefaction product yields in terms of condensable, non-condensable, and solid product

Yield of solid product



Yield of torrefied wood as a function of temperature and residence time *(Prins, Ptasinski et al. 2006)*

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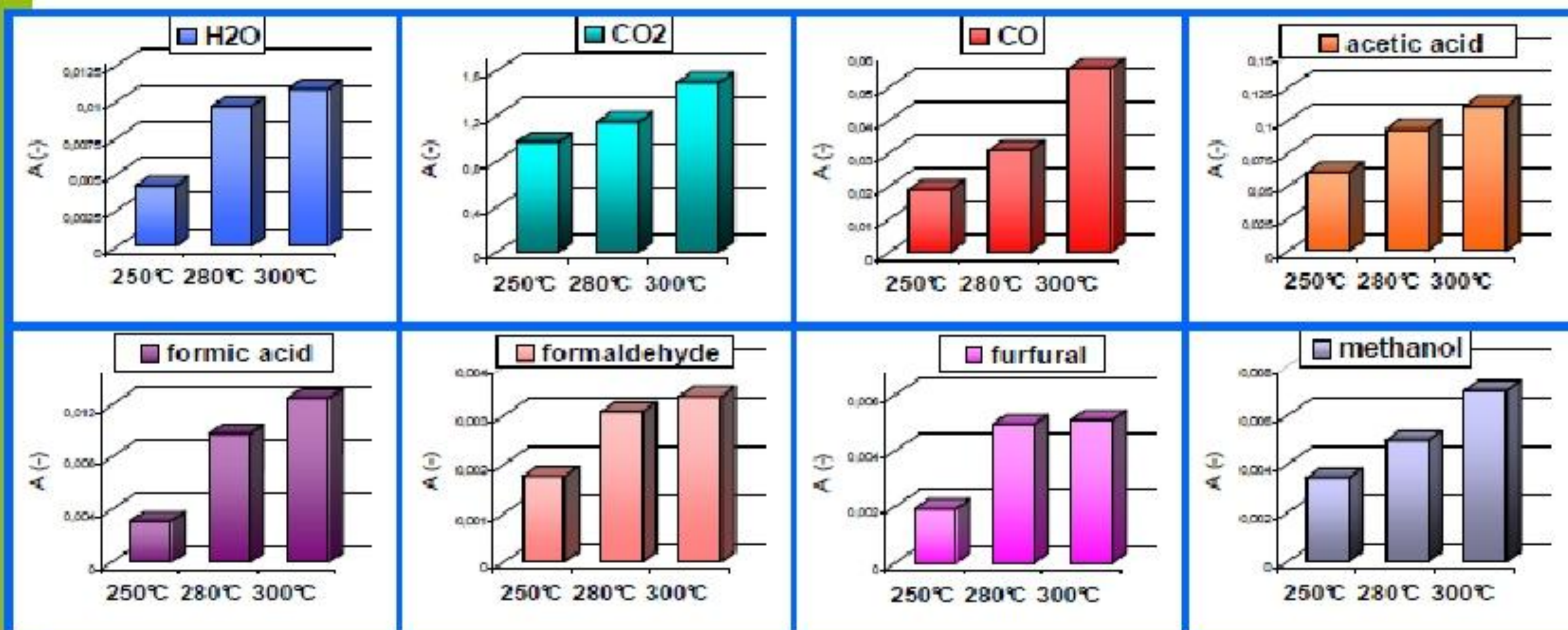
II - Torrefaction product yields in terms of condensable, non-condensable, and solid product

Gas species mean value vs temperature

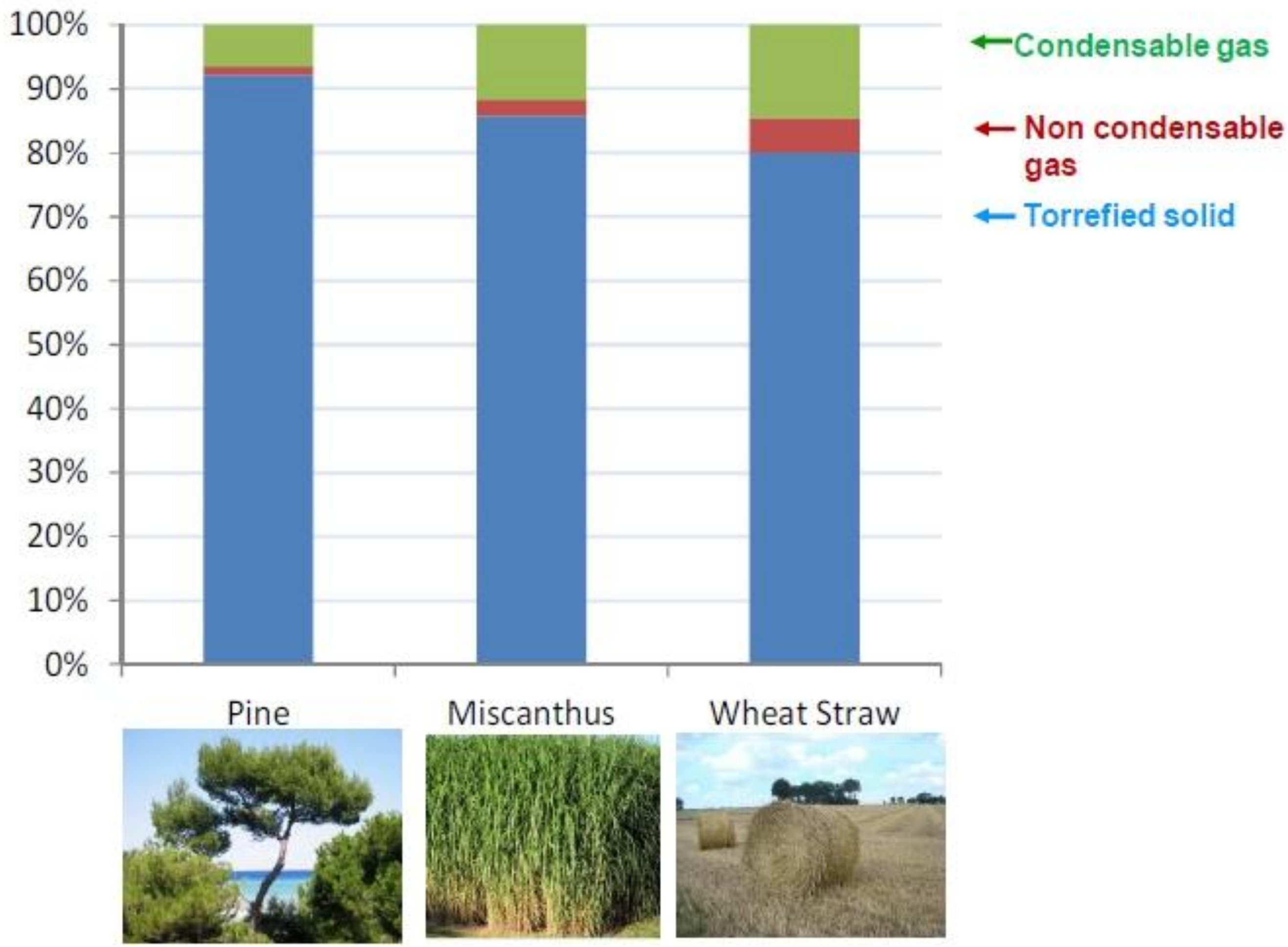


Increase of temperature → Increase of each gas yield

(Nocquet, 2010)

II - Torrefaction product yields in terms of condensable, non-condensable, and solid product

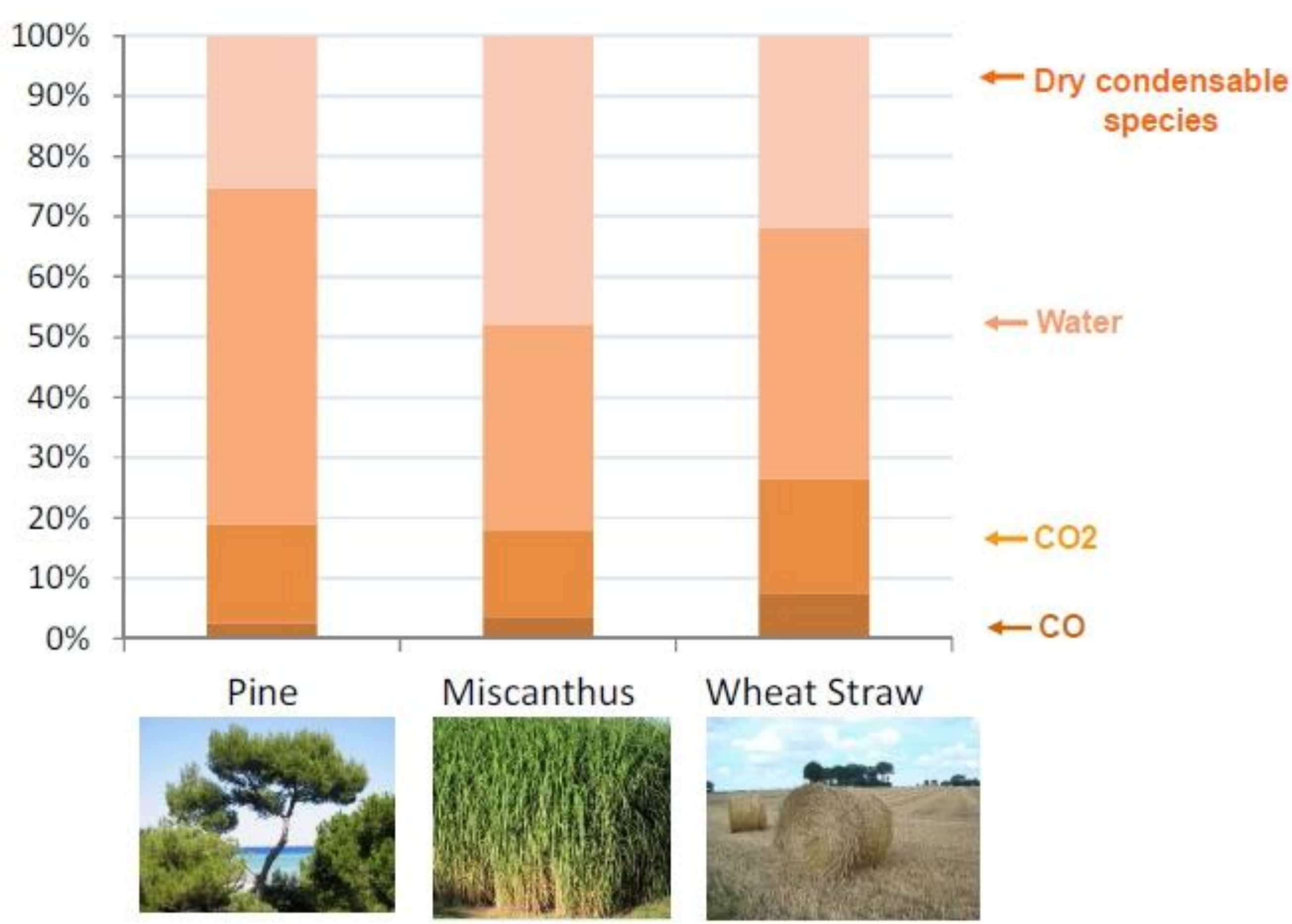
Global mass balance (250° C)



Conversion of woody biomass compare to agricultural residues (wheat straw) is much higher under the same torrefaction condition (Commandré.J.M, 2012)

II - Torrefaction product yields in terms of condensable, non-condensable, and solid product

Mass balance: volatile species (250° C)

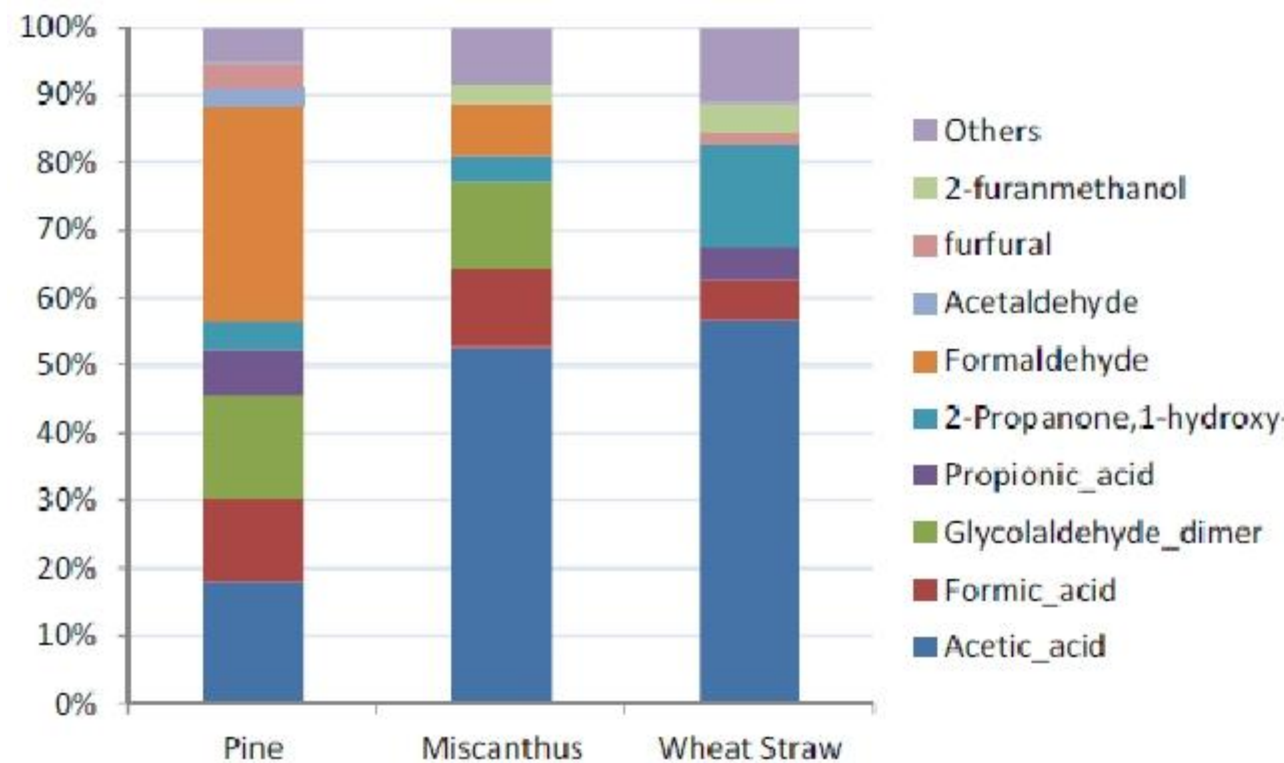


Similar non condensable gases, but differences in condensable species composition

(Commandré.J.M, 2012)

II - Torrefaction product yields in terms of condensable, non-condensable, and solid product

Mass balance: dry condensables species (250° C)



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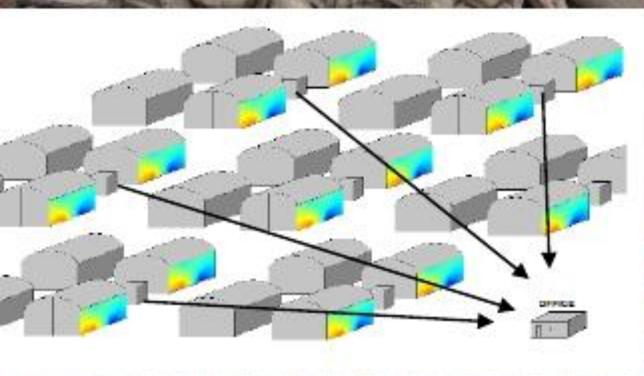

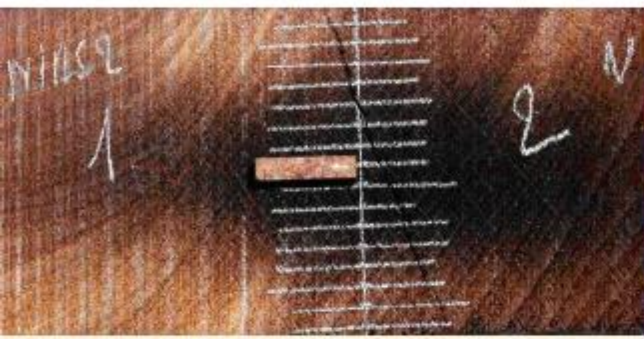

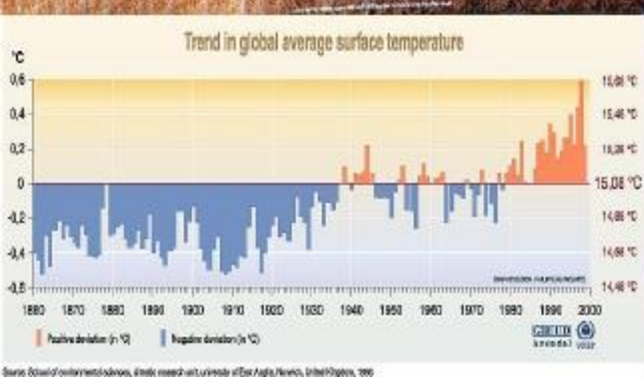

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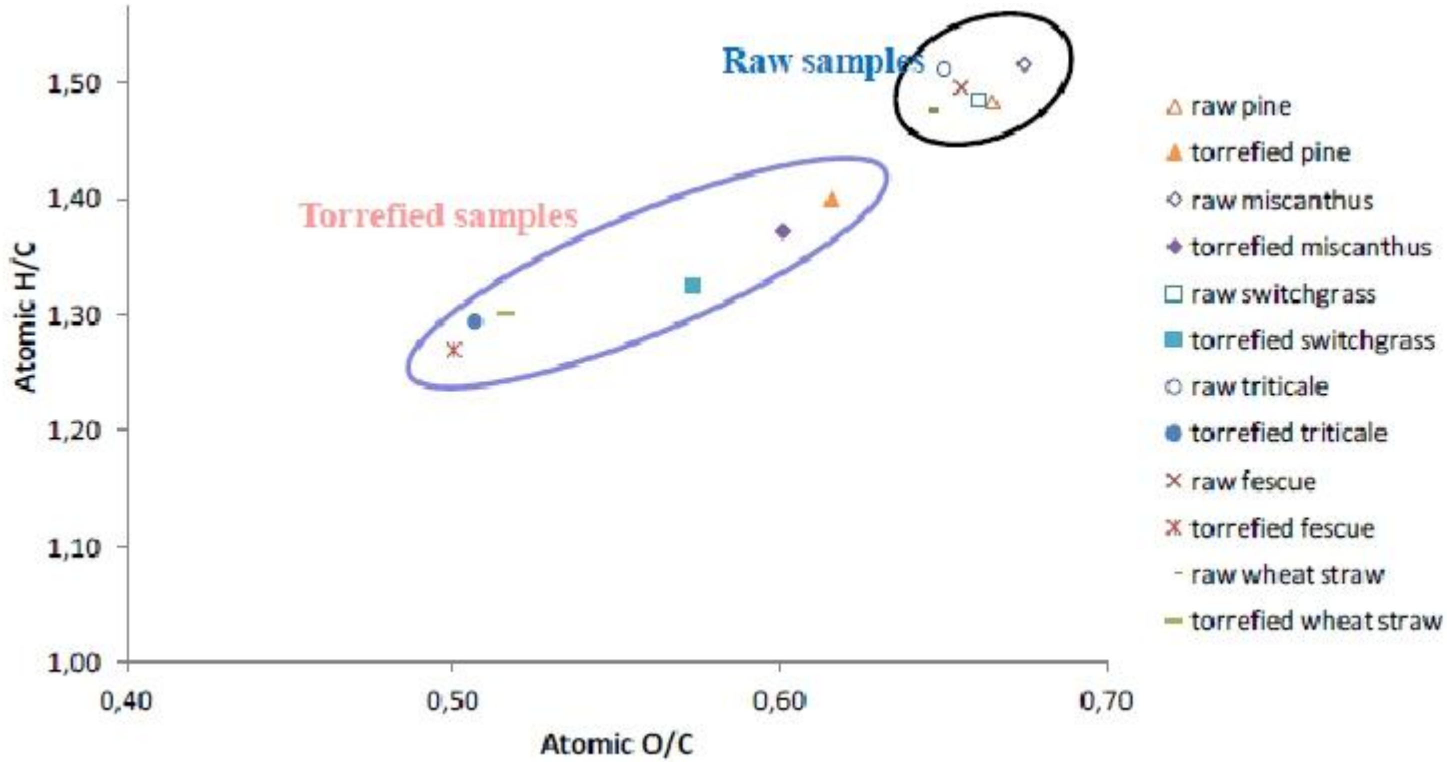
Torrefied solid composition



• During torrefaction, hydrogen and oxygen included in biomass are released. Ratios of H/C and O/C decrease when the heat treatment increases.

• Ratios H/C and O/C are similar for all raw biomasses

• Torrefied solids have lower ratios than raw biomasses

(Commandré.J.M, 2012)

III - Solid torrefied product's physical, chemical

Bulk density

Treatment	Bulk density (g/cm^3)	Percentage loss (%)
Control*	0.85a	—
T2 – 220°C	0.83a	2.35
T3 – 250°C	0.79b	7.06
T4 – 280°C	0.73c	14.12

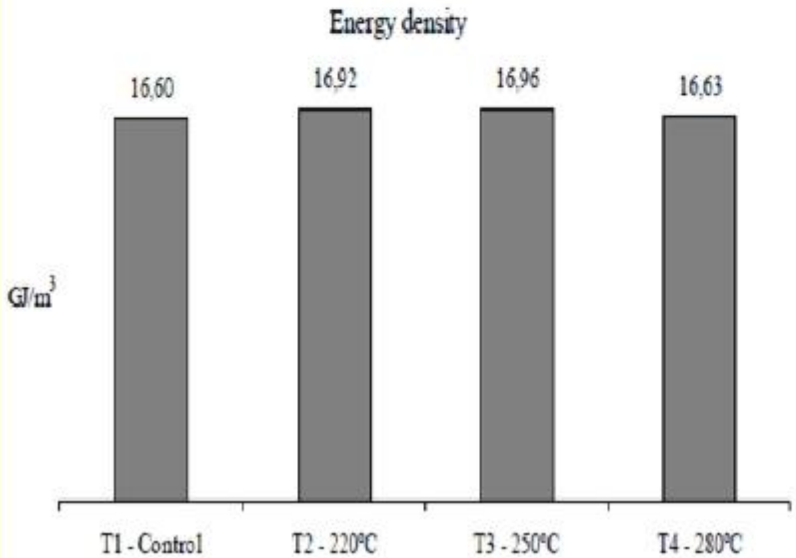
Note: Means followed by the same letter are statistically similar at the 5% probability level.
* Average moisture content of control treatment = 15%.

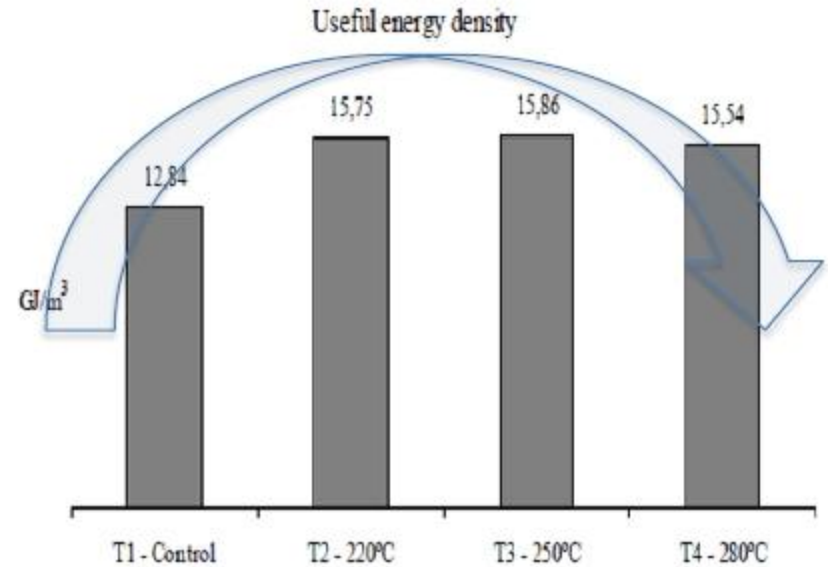
Mass loss in the form of solids, liquids, and gases during torrefaction cause the biomass to become more porous. This results in significantly reduced volumetric density typically between 180 and 300 kg/m3, depending on initial biomass density and torrefaction conditions

(Rodrigues and Rousset, 2009)

III - Solid torrefied product's physical, chemical

Energy density





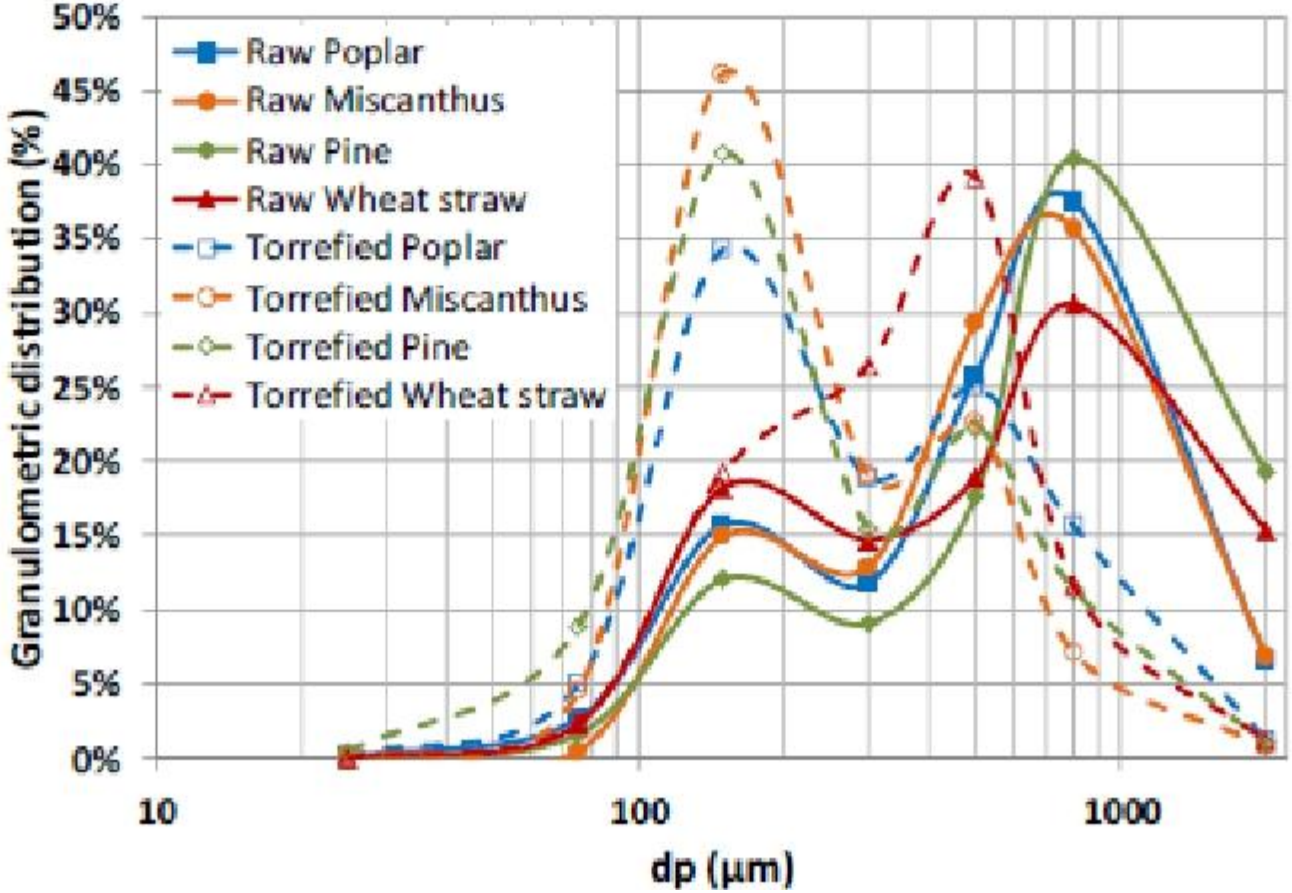
Energy density is related to the bulk density to the heating value of the biomass. Useful energy density (useful ED) related bulk density to useful heating value from untreated wood (UHV).

PCI ↗ Useful energy density ↘

(Rodrigues and Rousset, 2009)

III - Solid torrefied product’s physical, chemical

Particle size distribution

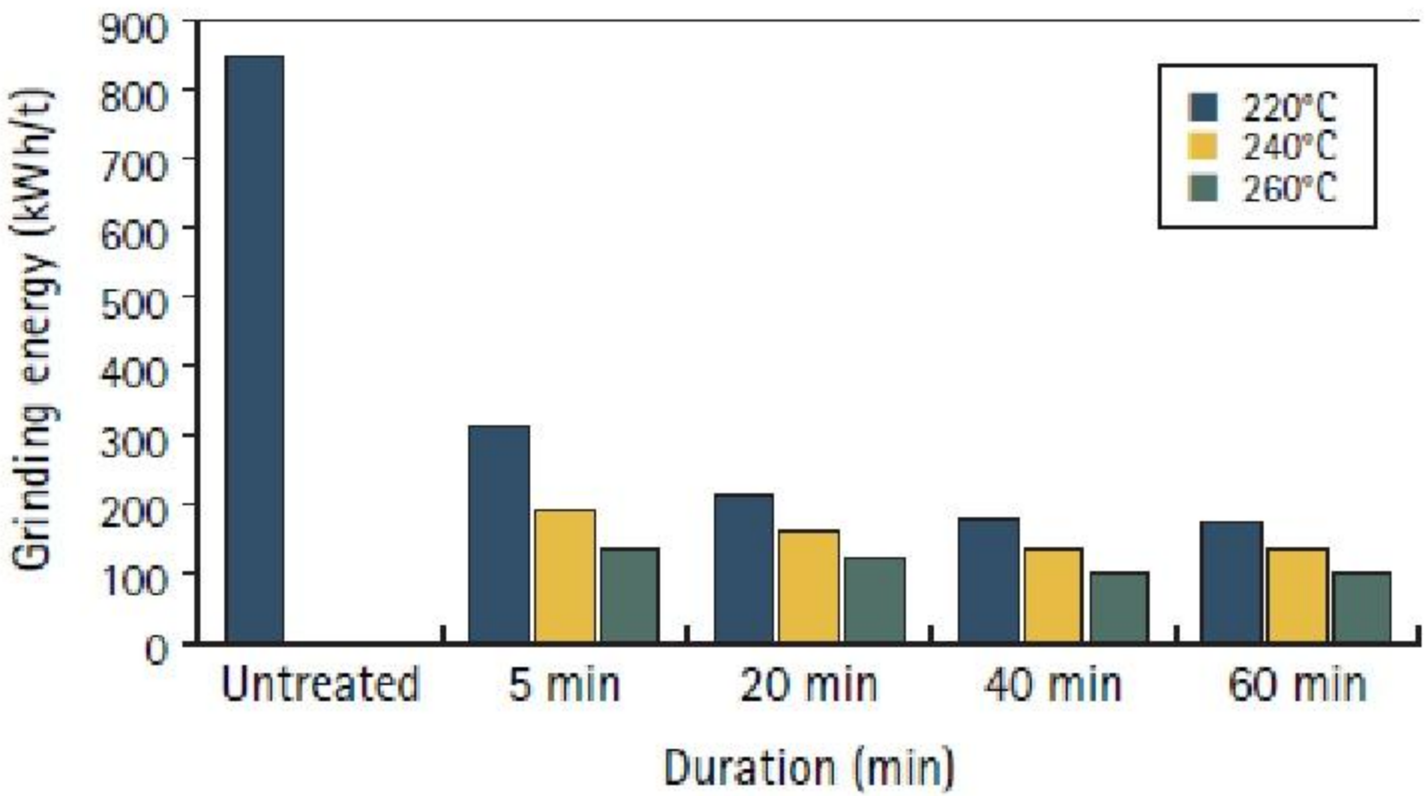


Torrefaction pretreatment reduces particle size distribution

(Commandré, 2012)

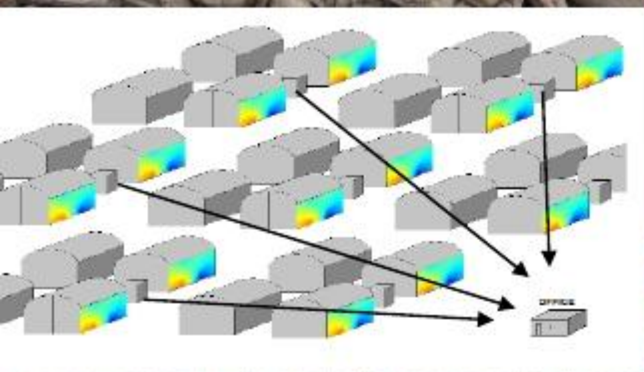
III - Solid torrefied product’s physical, chemical

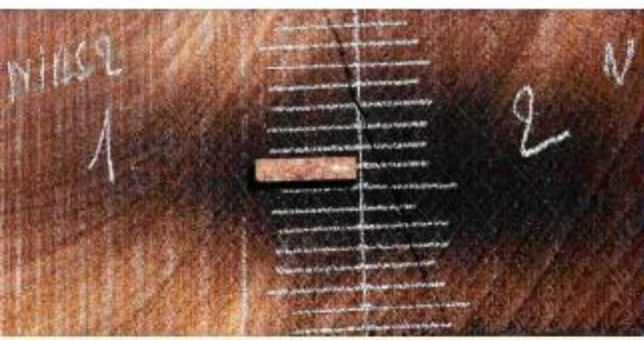
Grindability

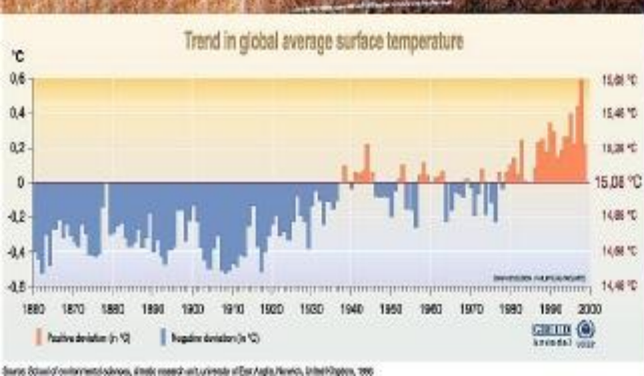


Torrefaction pretreatment reduces grinding energy consumption

(Rodrigues and Rousset, 2019)







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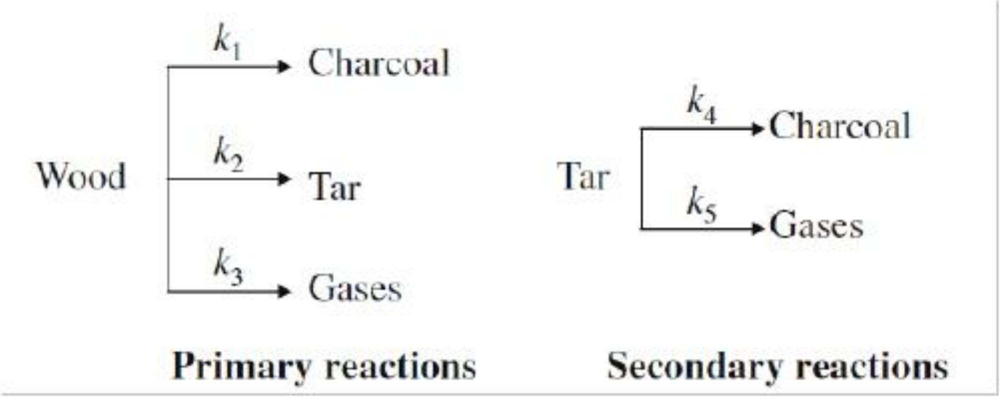
IV - Model

Two different approaches are used in modelling the pyrolysis of biomass:

➢ Predicting the total behaviour of wood starting from the evolution of its principal components according to the following equation:

Wood = %cellulose + %lignin + % hemicelluloses

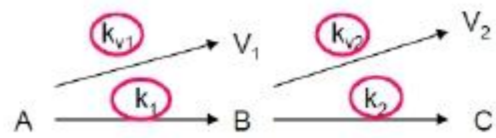
➢ The second method, called the "Lumped ParameterApproach", is more of a global strategy that consists in classifying the products resulting from the degradation of biomass



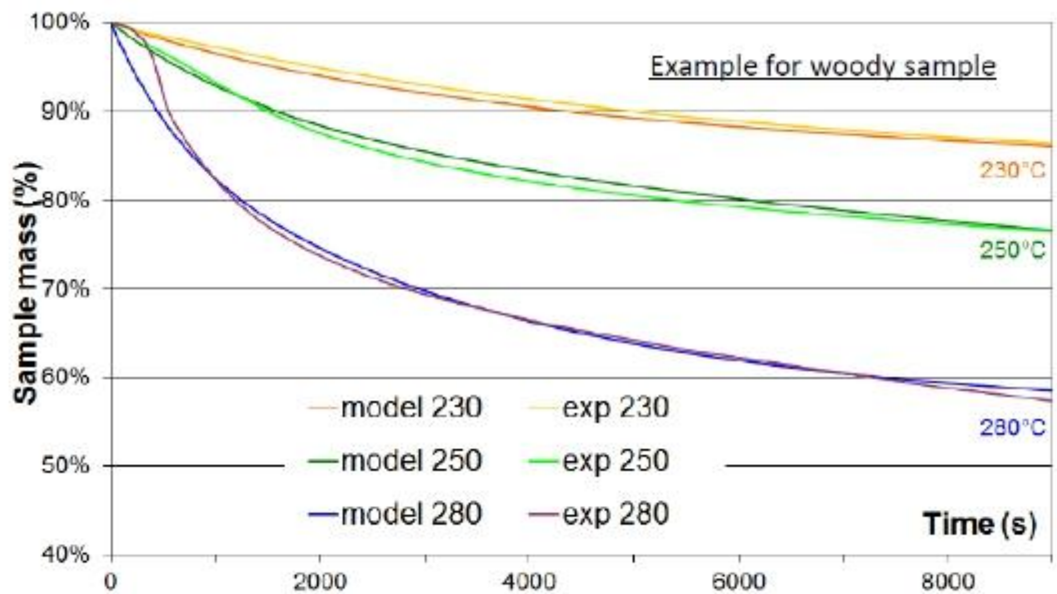
IV - Model

Simpler models appear to be suitable and more easily

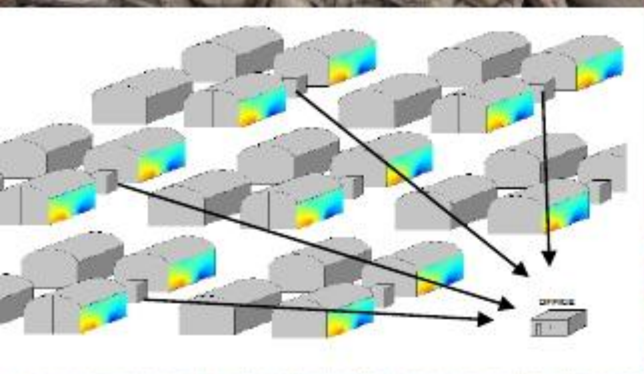
- 2 steps
- 2 parallel reactions
- First-order kinetics
- Arrhenius law

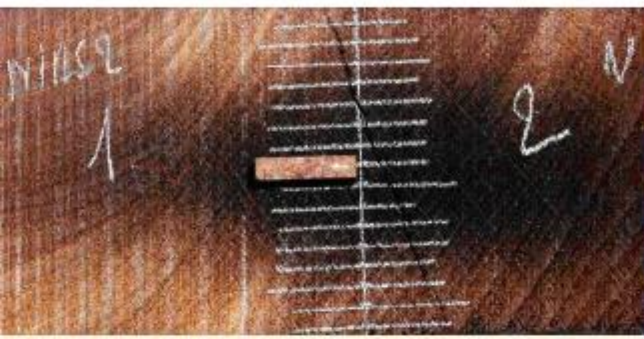


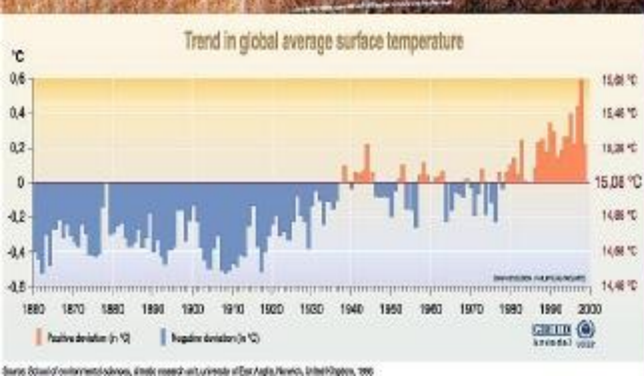
$$\frac{dm}{dt}=k_i\exp\left(\frac{-A_i}{RT}\right)m$$



Comparison model/experiment with woody biomass using the Diblasi Lanzetta Model (Commandré et al, 2012)







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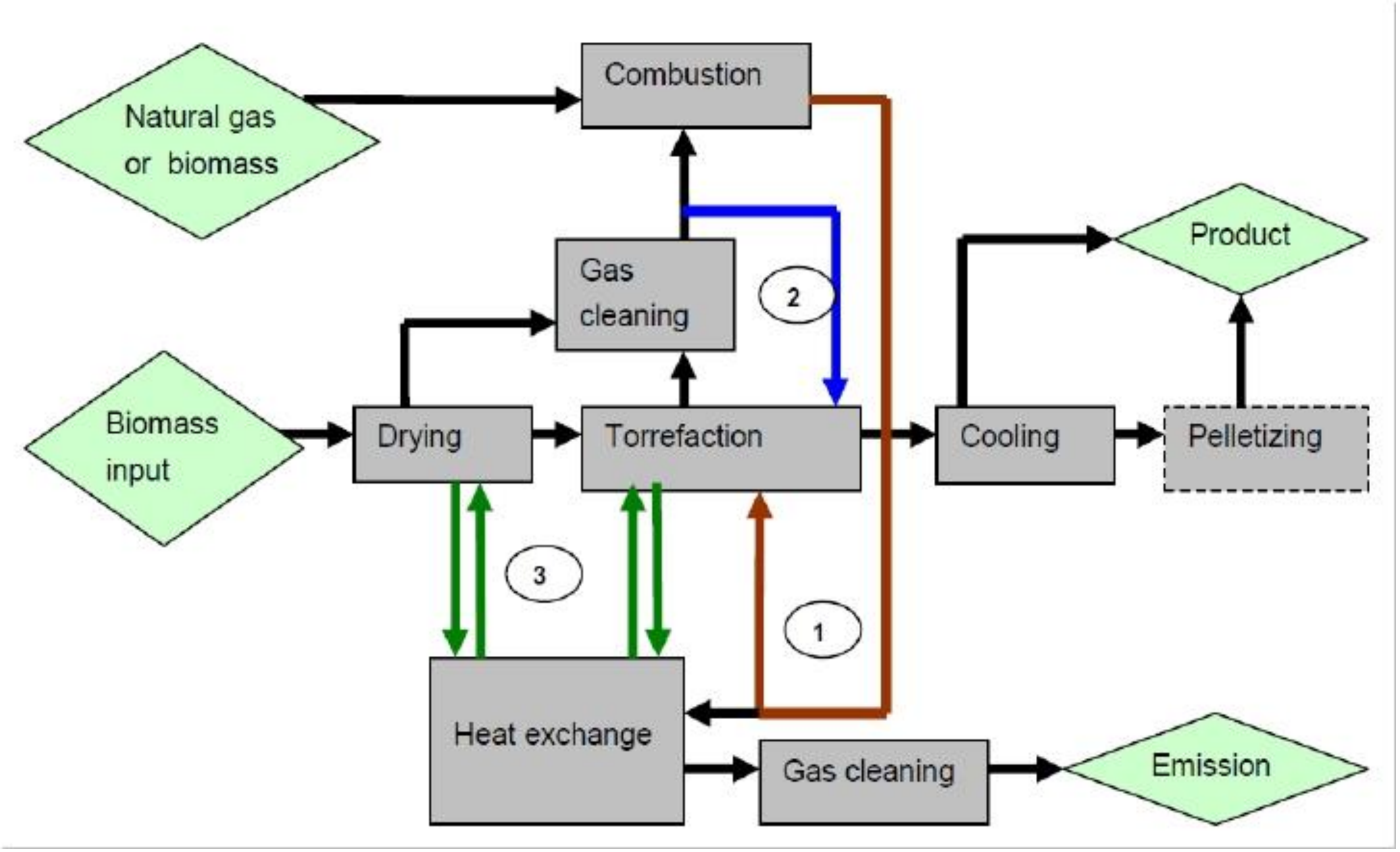
Atypical torrefaction process is presumed to comprise:

- drying of the biomass feedstock to have a biomass feed of constant moisture content to torrefaction.
- constant heat duty to be delivered to the torrefaction reactor
- a combustible torrefaction gas

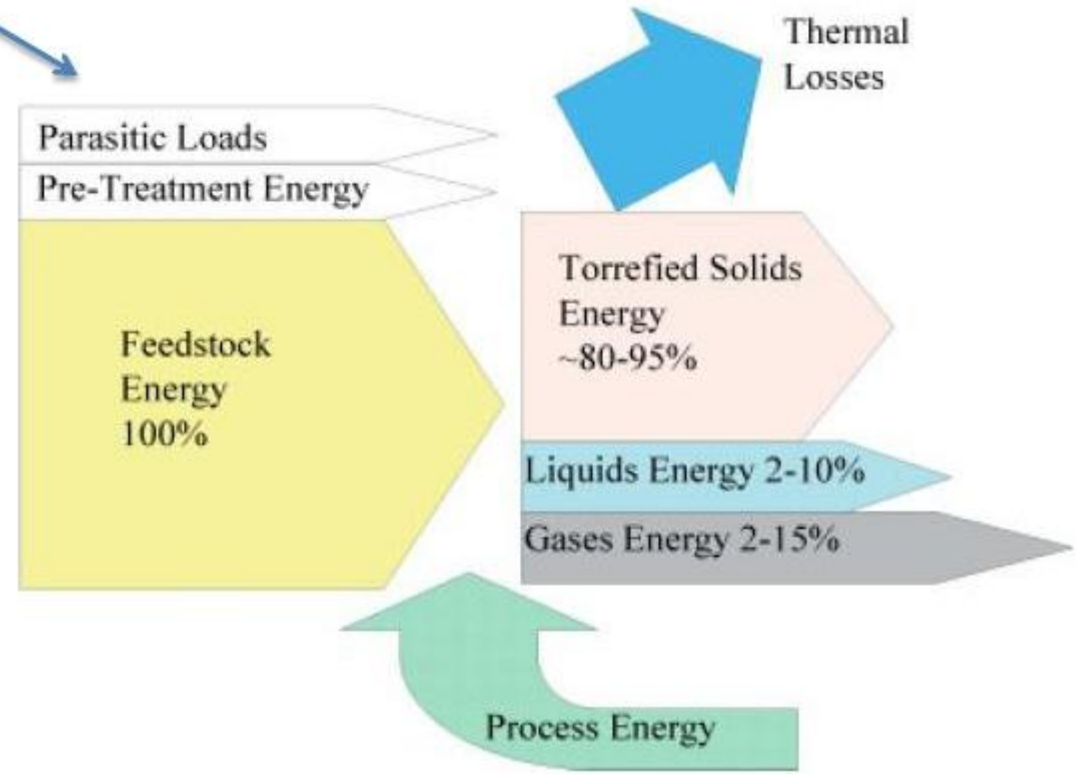


Heat integration option of torrefaction (Kleinschmitt, 2011)

V - Technologies

Energy inputs required to operate the torrefaction equipment (fans, pumps, etc.),

Chipping and or grinding,
and drying.

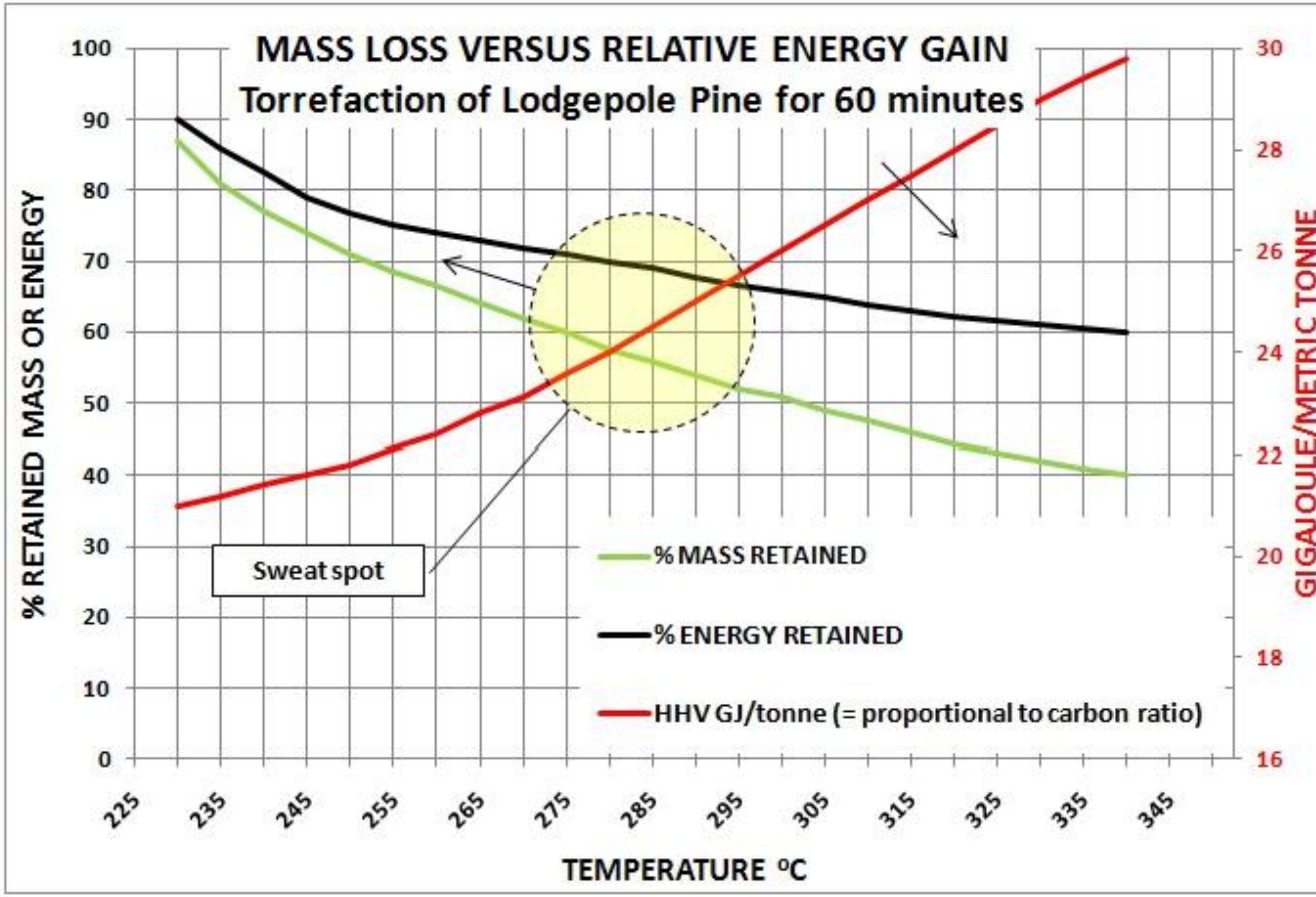


Energy balance of torrefaction process, assuming isenthalpic reaction.

(D Cielkosz, R Wallace, 2011)

V - Technologies

Alot of engineering has been done to improve heat recovery and to lower the energy consumption of the process

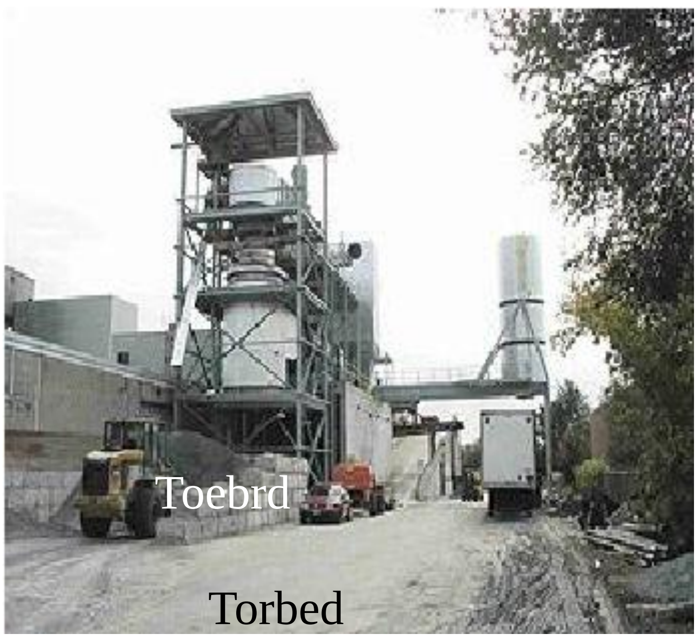


Mass loss vs relative energy gain (Melin, 2011)

V - Technologies


Rotating fluidized bed


Screw oven


Toebrd

Torbed


Multiple heat furnaces

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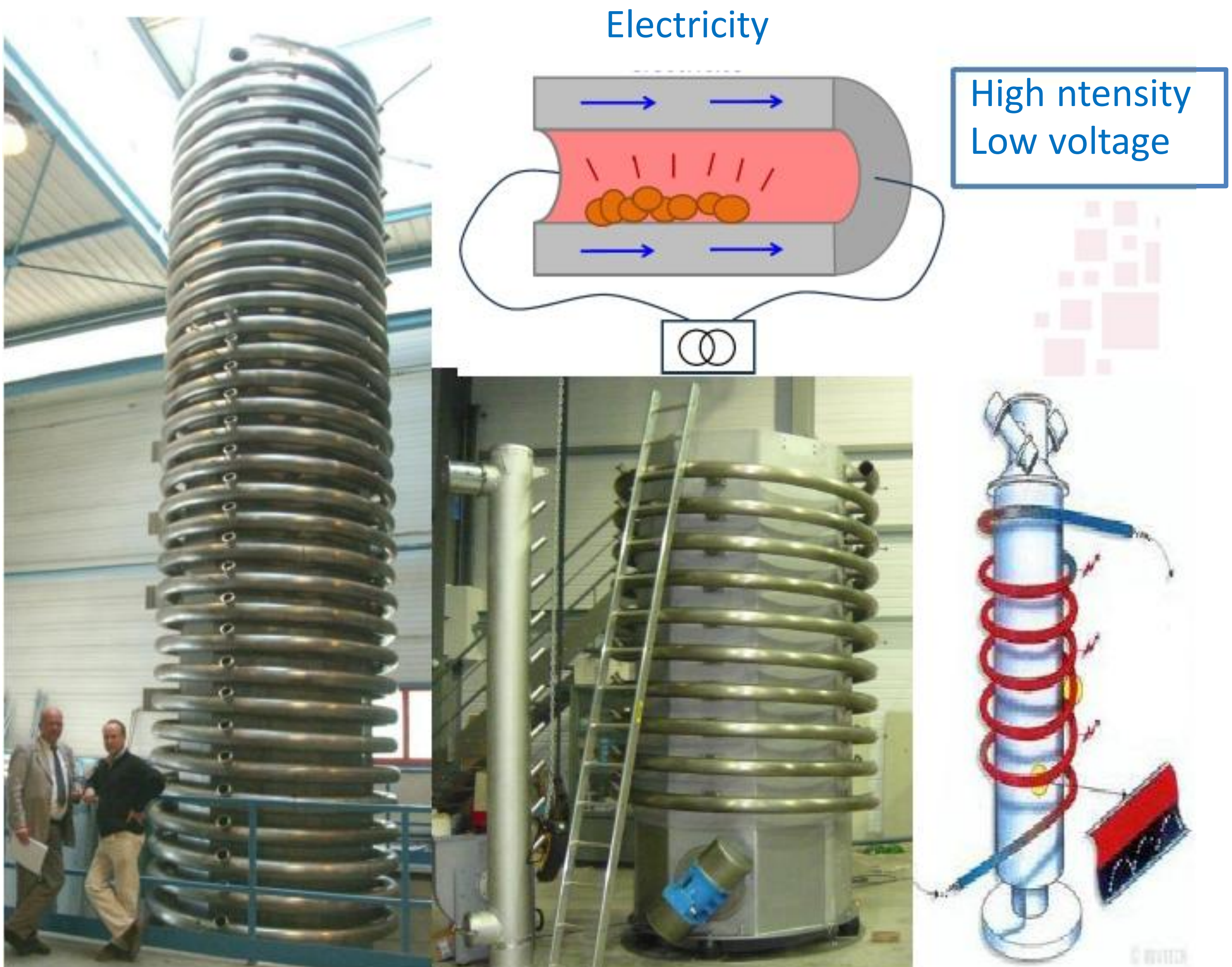
V - Technologies



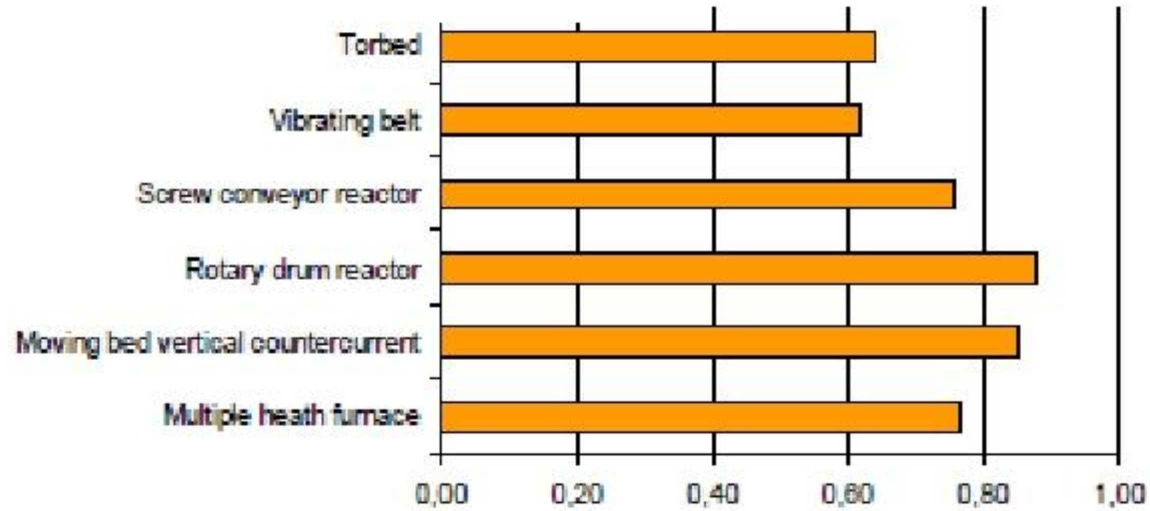
Closed spiral tube by vibrations and Heating by direct contact with an electrical impedance tube (Revetech process)

(Rousset, 2012)

V - Technologies

- General criteria : energy efficiency, mechanical complexity of installation and ease in scaling-up
- Constraints linked to process operation : control of temperature and resistance time, sealing
- Constraints linked to feedstock processing : nature of biomass, fines, chips acceptance
- Constraints associated with by-products processing : tars, corrosion resistant, easy cleaning

Overview of torrefaction technology: C.Casajus, F.Marias, P.Perard, B. De Guillebon, Albi, 2012



This assessment does not show a clear domination of one technology : all have advantages and disadvantages. Casajus and al (2012) showed in their study (no evaluation of Revetech process) the rotary kiln and the vertical countercurrent moving bed seem to be the most promising.

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