UNIVERSITY OF TRENTO

Department of Civil, Environmental and Mechanical Engineering
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Project of Thermochemical Energy Processes

Electrical energy production from biomass

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Chapter 1

Introduction

In Italy there are many co-generative system based on biomass that enable primary energy savings with respect to the separate production of heat and power [1].
The main objective of this work is the assessment of four biomass used as feedstock for an hypothetical co-generator system. To improve these analyses, it was used Aspen Plus software, which requires assessments about the chemical composition of biomass, thanks to the data in proximate and ultimate analysis.
The system includes different stages with a final recycle of water in a steam power cycle. Firstly, it is necessary to dry the biomass in order to execute the reaction of combustion. The most important phase is the assessment of chemical parameters in different point of this system, because of monitoring the vapor diffusion and quantify ashes created. Another aspect could be about turbine, capacitor, and pump works; it will be very important to optimize these combination of elements during the recycle of water by the steam.

1.1 Biomass

The principal aim of this analysis is the comparison of three biomass with the municipal solid waste (MSW), used as feedstock for energy production. Today, MSW is one of the most important energy source for some industry; it consists of human activity waste, in particular, on the cities, such as solid waste, waste water, rain outflow, and radioactive waste [2]. Therefore, there are different ways to deal it and European Union defined with the Directive n.2008/98/Ce of November 19th 2008 "any substance or object which the holder discards or intends or is required to discard". In this case, MSW represents the category of municipal waste, which contains many elements, such as sodium, chlorine, nitrogen and sulfur.
The data of MSW used for this work are from Germany, it is composed by sewage sludge, demolition wood, shredded rubber tyres, plastic and paper fluff [3].

The three biomass chosen are now accounted:

Olive trimming The phase of trimming at the end of the process of olive harvesting is important for the production of fruits. In Sicily, the production of residual agro-industrial biomass sums up to approximately $2.2\,Mt$ per year [4]. More specifically, olive cultivation and the olive oil industry generate more than $32\,kt$ of olive oil and approximately $160\,kt$ of olive waste every year. In addition, the pruning of olive trees implies the availability of substantial amounts of trimmings [4]. The best period to prune olive trees is between winter's end and flowering, therefore, in spring or in early summer once the olive trees begin to open its flower buds.

Grape marc It is the grape's residue which is rejected after the process of pressing in the wine production, it is separated from the pulp. Grape marc is usually used on grappa production or on the cheeses conservation. There are different kinds of grape marc, such as fermented, virgin, or sweet.
People from academia and industry are looking for new opportunities for the exploitation of the fresh (and also exhausted) grape marc. Some of them analyze the extraction of valuable compounds (polyphenolic compounds and grape seed oil in primis but also cellulose and hemicelluloses), others analyze the composting [5].

Bark pine It is one of main scraps from woods. *Pinus pinea* is the scientific name of Pinacee family, it is diffused on Mediterranean Basin, primarily on northern coasts.
People use bark pine on garden for mulching properties, or rather the use of natural waste and foliage to have best garden qualities. Often, it is sold with a mixture of different kinds of wood [6].

Chapter 2

Methods

2.1 Proximate and Ultimate Analyses

Feedstock dataset has been found on two scientific articles and online *phyllis database*: there are some articles about olive trimming [4] and grape marc [5] utility in waste form, for instance for the development of energy systems. Therefore, it has been chosen to analyze these materials in a co-generation system for the production of heat and electrical power.
Table 2.1 shows ultimate analyses, in which weight percentage of carbon, hydrogen, nitrogen and sulfur are reported:

Components	Olive trimming	Grape marc	MSW	Bark pine	Molar mass (g/mol)
C	48.30	54.90	49.23	53.90	12.011
H	6.10	5.83	8.15	5.80	1.008
O	40.00	32.70	22.27	38.26	15.999
N	1.50	2.09	1.82	0.40	14.007
S	0.00	0.21	0.25	0.03	32.060

Table 2.1: Ultimate analysis of selected biomass, on a dry basis [6].

Starting from ultimate analysis, it is possible to know these percentage, whereas, the Proximate Analysis gives moisture content, volatile content, fixed carbon remained, ash and higher heating value (HHV). The *table 2.2* presents all Proximate Analysis data for each components:

Content	Olive trimming	Grape marc	MSW	Bark pine
Moisture (%)	4.30	8.00	6.16	5.00
Volatile (%)	78.40	32.70	72.6	71.80
HHV (MJ/kg)	19.80	21.80	20.48	28.38
Ash (%)	4.00	4.27	16.82	1.60
Fixed C (%)	17.60	63.03	10.58	26.60

Table 2.2: Proximate analysis of selected biomass, on a dry basis [6].

On both *table 2.1* and *table 2.2* it is important to note that a higher carbon content causes a greater HHV. When there are specification components it is necessary to set all kinds of analysis, called

proxanal for proximate, *ultanal* for ultimate, and *sulfanal* for sulfur ratio; this passage helps to identify ash content.
The moisture levels of proximate analysis are calculated after the process of drying, so they can be considered as *residual* moisture.

2.2 Air flow rate required for combustion

The first step is to find xyz values in biomass molecular formula, using the dataset on *tables 2.1 & 2.2*. In fact, selected biomass are represented by their own formula

- olive trimming: $C_{4.0213}H_{6.1508}O_{2.5001}$
- grape marc: $C_{4.5708}H_{5.7837}O_{2.0439}$
- MSW: $C_{4.0987}H_{8.0853}O_{1.4832}$
- bark pine: $C_{4.4875}H_{5.7539}O_{2.3914}$

In order to calculate the minimum quantity of oxygen for the complete combustion of biomass, the *equation 2.1* is used an excess of air $\%EA = 0$.

$$\begin{aligned} C_xH_yO_z + \left(\frac{\%EA}{100}+1\right)\left(\alpha+\frac{\beta}{4}-\frac{\gamma}{2}\right)\left(O_2+\frac{79}{21}N_2\right) \rightarrow \\ \rightarrow \alpha CO_2 + \frac{\beta}{2}H_2O + \frac{79}{21}\left(\frac{\%EA}{100}+1\right)\left(\alpha+\frac{\beta}{4}-\frac{\gamma}{2}\right)N_2 + \left(\alpha+\frac{\beta}{4}-\frac{\gamma}{2}\right)\frac{\%EA}{100}O_2 \end{aligned} \tag{2.1}$$

In this way, it was calculated the minimum quantity of oxygen for combustion: for each biomass, $100\,g$ are assumed and the correspondent mass of carbon. It is known that the molar mass of carbon is around $12\,g/mol$, so it was calculated how many moles of carbon are present in a kilogram of total biomass. Through a stoichiometric approach, it is possible to know how many moles of oxygen are there in the biomass and, finally, how many kilos of oxygen is necessary to burn the biomass.
In a combustion reaction, it is necessary to work with excess of oxygen, therefore, it was considered an increasing of $30\,\%$ of oxygen by the minimum ratio. Through this, it was known the input air flow to the reactor considering $21\,\%$ of oxygen and $79\,\%$ of nitrogen.
Finally, the amount of air mass required to burn $1\,kg$ of biomass is calculated:

- olive trimming: $1.3788\,kg_o/kg_{bm}$
- grape marc: $1.5983\,kg_o/kg_{bm}$
- MSW: $1.7211\,kg_o/kg_{bm}$
- bark pine: $1.5137\,kg_o/kg_{bm}$

2.3 Aspen Plus ®

Process simulation with Aspen Plus allows to predict the behavior of a process using basic engineering relationships such as mass and energy balances, phase and chemical equilibrium and reaction kinetics. Given reliable thermodynamic data derived from real plants and the rigorous Aspen Plus equipment models, actual plant behavior can be simulated. It can help the stage of designing plants and increasing profitability in existing plants.
Through Aspen Plus, it is possible to interactively change specifications, such as flowsheet configuration, operating conditions, and feed compositions, to simulate new cases and analyze alternatives. In order to analyze the results, Aspen Plus can generate plots, reports, PFD-style drawings, and spreadsheet files [7].

Firstly, the approximated scheme for biomass treatment is designed (*figure 2.1*). It is featured by the reactor with water and biomass, an heat exchanger to heat up the steam, and two users: the turbine and the capacitor, which can produce work and heat, respectively. For this first scheme is not necessary to have a recycle because we can monitor parameters in the starting point, flue gases and exiting water.

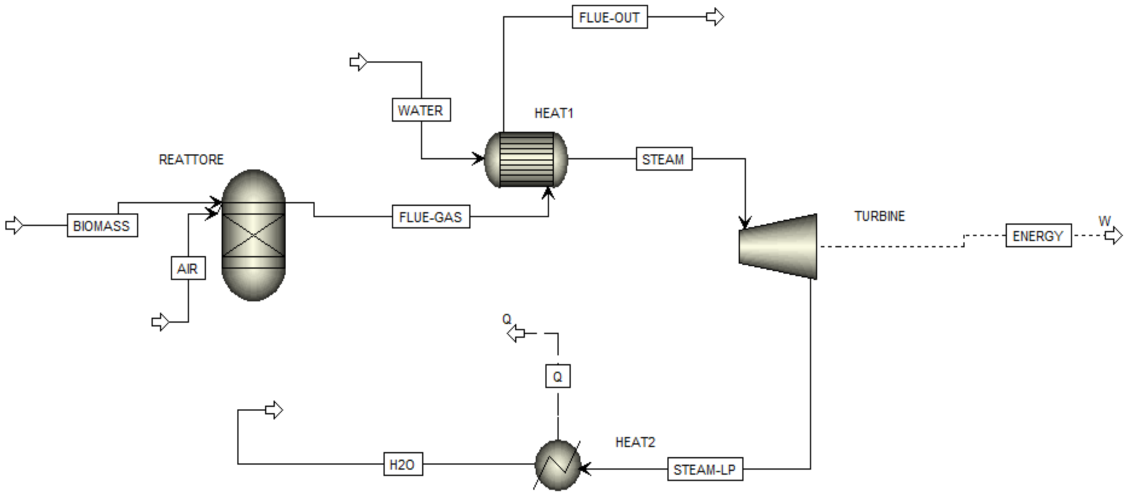

Figure 2.1: First scheme of flow-sheet.

Then, the scheme is improved with links between ideal *Blocks*. Of course, it is not possible to have a detailed representation of the real components, but Aspen Plus can recreate the real conditions of parameters, such as temperature, pressure, stream composition.
In the *figure 2.2* is represented the final scheme of the steam power plant. The process is characterized by two main elements: the combustion chamber and the steam cycle. The first stage is used to produce hot flue gases, contained in the flue gases, by burning the biomass with an excess of air of the 30 %. The second stage produces mechanical work by using the enthalpy difference of the gases to heat a stream of steam water in the heat exchanger, which is then expanded in the turbine. At the beginning a *decomposer block*, working at combustion temperature, is used to split the biomass in its constitutive elements, with the data provided by ultimate and proximate analysis. Then the biomass

enters the combustion chamber at 900 °C together with the stream of air. The flue gases resulting from the process are separated from the ashes in the *separator block*, which separates solids from gases.

The ash free flue gases cleaned from the ashes exchange heat with high pressure water to generate steam at high temperature, which expands in a turbine producing mechanical work, which will be transformed into electrical power. In the steam cycle, a pump is used to increase the pressure of water up to $8\,bar$ and an heat exchange is used to recover heat from the steam and to condensate it into liquid phase. The turbine discharges steam water at $1\,bar$.

The drying stage is simulated in Aspen Plus' scheme by a separator, that is used to remove the moisture from the biomass. It should be noted that this process is not realistic because in real plants drying allows to reduce the moisture content only below the $10\,\%$ [4]. Proximate analysis provides data obtained from a dried feedstock, so it has been decided to simulate a "wet" biomass by making assumptions about the initial moisture content. Therefore, flux of water characterized by a percentage of the total flow rate of the biomass, equal to the moisture content lost in the drying system, joins the flux of biomass which will remain after the process of drying. This assumption is made to simulate the conditions of the biomass at the start of the process.

After the drying stage, *BIO-DRY* (*figure 2.2*) represents the biomass characterized by proximate analysis data seen in *table 2.2*; the moisture content calculated is residual content of water after drying.

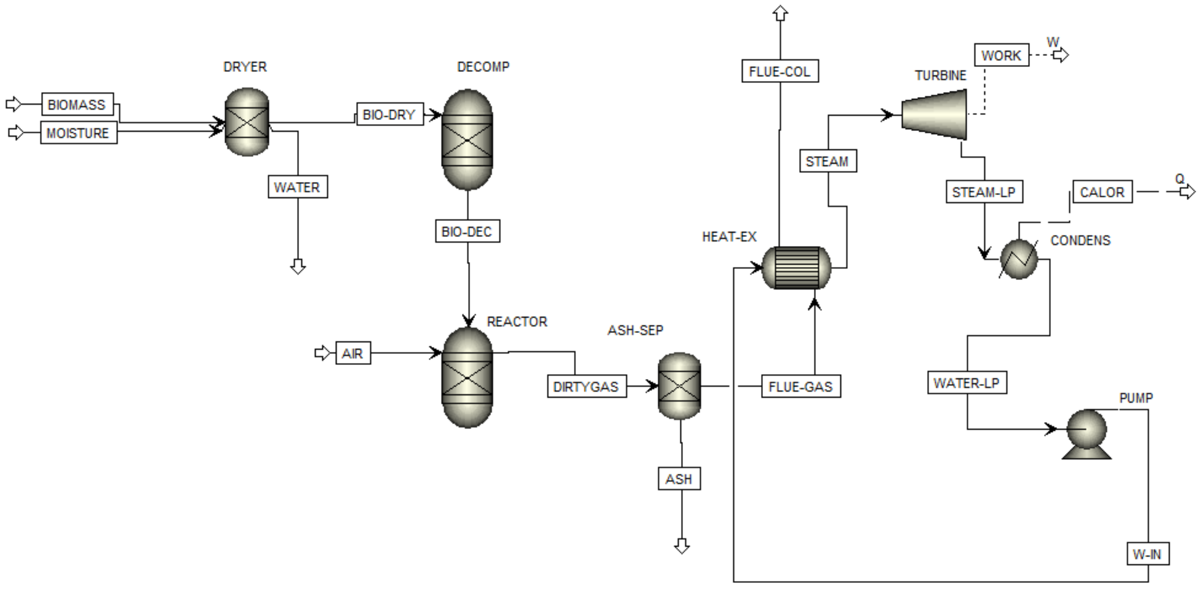

Figure 2.2: Final design of Flow-sheet.

2.4 Software input data

In the *table 2.3* the main parameters of the software are summarized, particularly regarding on steam cycle after the separation between ash and flue-gas.
Furthermore, the turbine for steam expansion is set as *isentropic* with an efficiency of about 80 %, and a hypothetical mechanical efficiency of 98 %.

Parameters	Values	
biomass temperature	20	°C
air temperature	20	°C
biomass pressure	1	bar
air pressure	1	bar
reactor temperature	900	°C
steam temperature	600	°C
water IN pressure	8	bar
steam LP pressure	1	bar
condenser temperature	20	°C

Table 2.3: Input parameters

Chapter 3

Results and discussion

Firstly, it is necessary to calculate the minimum oxygen ratio for a completely combustion for each biomass, through the method explained. Therefore, it is considered air ratio as input value, because it defines the flow of air in the reactor. Through stoichiometric approach, the results are explained on the *table 3.1*, with a feedstock input of $20\,kg/h$ as first approximation, using the formula cited on *paragraph 2.2*.

Biomass	Oxygen [kg_o/kg_{bm}]	Air [kg/h]
Olive trimming	1.3788	170.7159
Grape marc	1.5983	197.8894
MSW	1.7211	213.0896
Bark pine	1.5137	187.4118

Table 3.1: Flow air inlet.

Of course, these values are adapted in function of flue ratio biomass in the follow analyses. In fact, to understand differences between real cases of energy plant, a flow ratio of $200\,000\,kg/h$ is supposed for each biomass, and calculated the corresponding air.

Biomass	CO	CO_2	O_2	H_2	H_2O
Olive trimming	4.07E-09	1.78E-01	7.03E-02	1,92E-10	6.03E-02
Grape marc	3.72E-09	1.70E-01	7.68E-02	1.57E-10	5.15E-02
MSW	3.27E-09	1.47E-01	7.53E-02	2.01E-10	6.48E-02
Bark pine	4.08E-09	1.81E-01	7.19E-02	1.65E-10	5.24E-02

Biomass	N_2	NO	NO_2	S	H_2S
Olive trimming	6.91E-01	9,51E-05	1,49E-06	0	0
Grape marc	7.01E-01	1.00E-04	1.65E-06	1.48E-04	3.17E-05
MSW	7.12E-01	9.99E-05	1.61E-06	1,63E-04	4.38E-05
Bark pine	6.94E-01	9.63E-05	1.53E-06	2.27E-05	5.11E-06

Table 3.2: Flue-gas composition, mass fractions at combustion temperature of 900 °C.

3.1 Sensitivity analysis

A sensitivity analysis consists in the observation of fluxes composition or parameters variation due to the change of an environmental condition within a specific range, such as temperature. It is necessary to understand when and how some phenomena happen.

In fact, in this case, the first analysis regards the variation of temperature in the reactor, from 700 °C to 1200 °C. Due to this, flue-gas (output of reactor) changes its composition and it is possible to see the evolution of molecule products, such as carbon monoxide (CO), nitrogen oxide (NO), hydrogen sulfide (H_2S) and nitrogen dioxide (NO_2), because they could damage the environment or human health.

From *figure 3.1* it is possible to highlight the absence of hydrogen sulfide in the flue-gas due to the natural composition of olive trimming, in fact sulfur is not present. In the same time, other molecules increase in concentration with highest temperature, in agreement with thermochemical reaction. It is important to note that the nitrogen oxide has the highest concentration, about $6E-04$ in molar fraction with 1200 °C, while carbon monoxide and nitrogen dioxide are about $1E-06$.

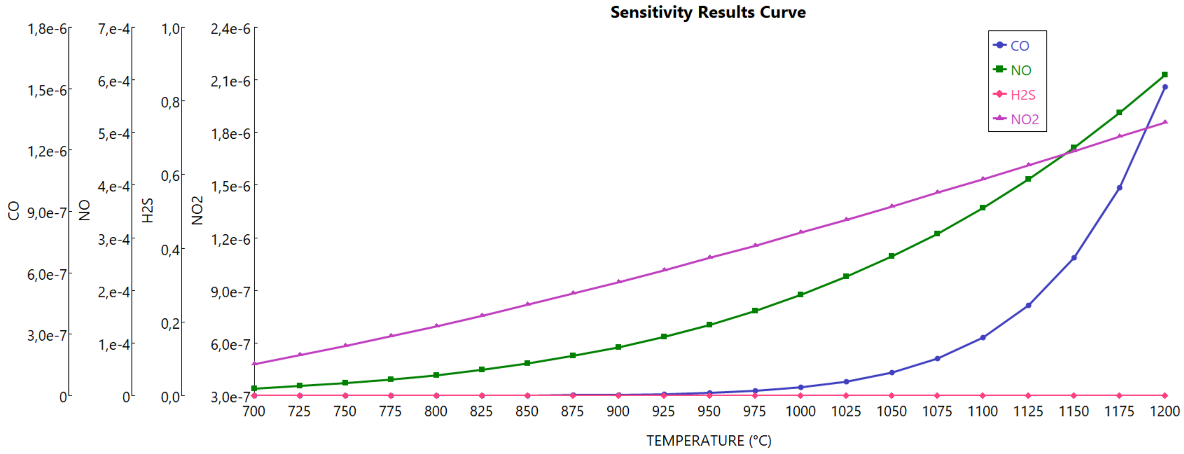

Figure 3.1: Molar fractions of olive trimming gas emissions, depending on temperature.

Instead, in *figure 3.2*, the grape marc sensitivity analysis result is represented. Due to natural composition, at low temperature there is a molar fraction of $6.5e-5$ hydrogen sulfide, its concentration decreases with temperature. Other components have similar behaviour in terms of concentration, with about the same order of magnitude.

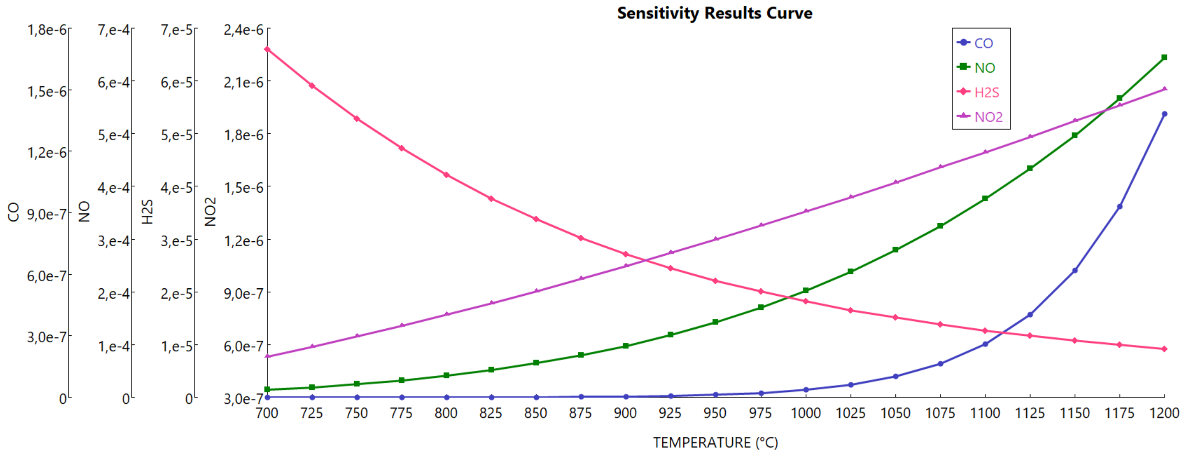

Figure 3.2: Molar fractions of grape marc gas emissions, depending on temperature.

For municipal solid waste, the results are represented in *figure 3.3*, where it is clear that the molar fraction of carbon monoxide is lower that the first two cases, because of lower value of fixed carbon content (*table 2.2*). Although, other molecules have similar values of concentration.

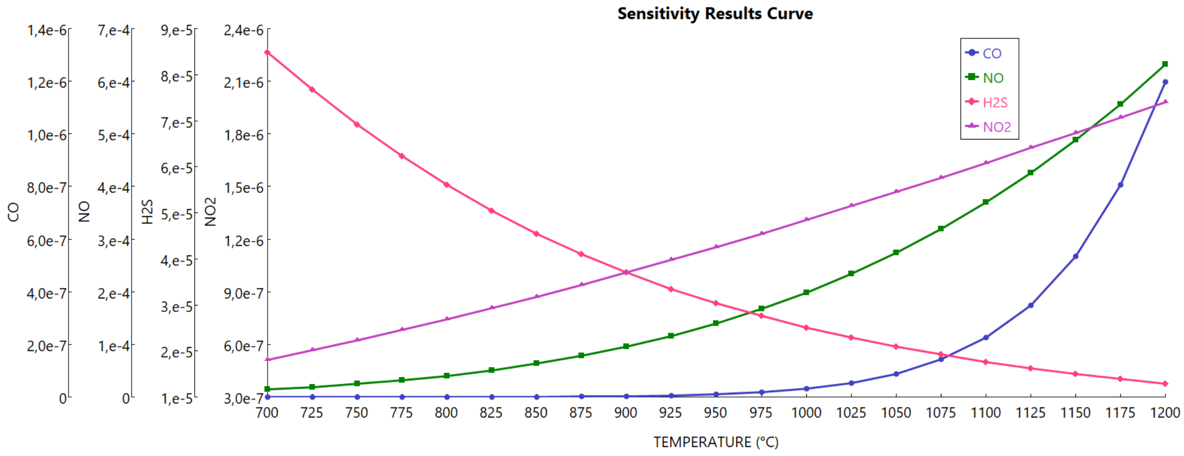

Figure 3.3: Molar fractions of MSW gas emissions, depending on temperature.

Finally, bark pine has the lowest concentration of hydrogen sulfide, due to small amount of sulfur in the natural composition. This is demonstrated by *figure 3.4*, also the similar trend of other molecules with temperature.

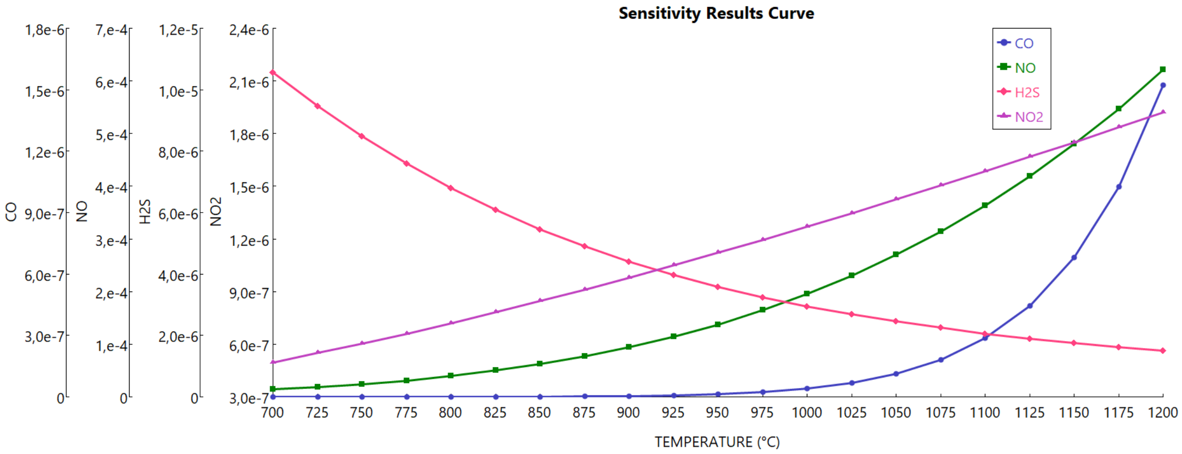

Figure 3.4: Molar fractions of bark pine gas emissions, depending on temperature.

Two main evidences are discussed: firstly, the trend of nitrogen dioxide is almost linear with the increase of temperature, in contrast other trends; secondly, working at temperature of 900 °C implies low emissions of these harmful gases.

The combustion of biomass is always an exothermic reaction, therefore, it produces heating. Through thermodynamic laws, every exothermic reaction has a negative enthalpy difference ($\Delta H < 0$), because the sum of reactants enthalpy is lower than the sum of products entalphy [8]. In fact, each graph of sensitivity analysis shows the increase of some gas molar fractions with the increase of temperature.

An important consideration is about hydrogen sulfide, which decreases in grape marc, MSW and bark pine. Regarding nitrogen oxides (NO_x), their molar fractions increase with temperature, due to the higher temperature of formation. Therefore, in according to the increase of NO_x the concentration of carbon monoxide increases, as an intermediate product of combustion. Every graph shows that over the temperature of about 900 °C the fraction of unburned products is relevant in terms of order of magnitude.

3.2 Power resulting from biomass

Analyzing the results of the simulations, due to a lower ratio of initial moisture, a higher flow rate of steam can be used. Between each simulation, the main difference in the power cycle is the value of steam flow rate, in order to reach a different level of power from the turbine.
In *table 3.3* comparisons between quantity and power are expressed. For each biomass it is used the same flow rate of about $200\,000 kg/h$.

Parameters		Olive trimming	Grape marc	MSW	Bark pine
Biomass flow	$[kg/h]$	200 000	200 000	200 000	200 000
Moisture	[%]	50	50	10	40
Steam flow	$[kg/h]$	50 000	50 000	90 000	60 000
Power output	$[MW]$	7.30	7.30	13.15	8.76

Table 3.3: Powers due to fixed flow rate.

In *table 3.4* the biomass quantities needed to reach the power of a large size steam plant which provides $20MW$ of electrical energy.

Parameters		Olive trimming	Grape marc	MSW	Bark pine
Biomass flow	$[kg/h]$	600 000	600 000	320 000	466 667
Steam flow	$[kg/h]$	150 000	150 000	144 000	140 000
Power output	$[MW]$	21.91	21.91	21.03	20.45

Table 3.4: Biomass needed to reach about $20MW$.

Chapter 4

Conclusions

In this work, a process for the electrical production was simulated with a set of feedstock of biomass. These were compared between themselves and municipal solid waste, which was used in several large size industry through combustion processes. Starting from the composition of the investigated biomass, it was possible to assess flue-gas emissions and turbine power production, to answer at the main question "which biomass is the most suitable for energy production?". Through Aspen Plus the process of combustion and explained results with graphs was simulated. Main differences are highlighted through the last simulation, with real quantities of biomass, and finding a real power of large size industry.

Regarding the flue-gas composition, the analyzed harmful molecules are present in low concentration at 900 °C, in fact, this is the optimum of working temperature. It is necessary to note that sensitivity analyses are achieved with a biomass flue rate of $200\,000\,kg/h$.

From the software results, it is clear that municipal solid waste is the most suitable feedstock for a steam plant due to the low moisture level, however, this is not a natural feedstock such as biomass. Therefore, bark pine is the best of the selected biomass, because of lower humidity and the availability from wood industry and its highest HHV. In fact, grape marc and olive trimming are seasonal products, so they are less suitable for generation of electrical power in a large size plant. A good idea will be to use them as energy recovery in the same factory where those are produced, such as wine or oil companies.

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