THESIS

Master of Science in Energy Technology

Karlsruhe Institute of Technology

Techno-economic evaluation of an intermediate pyrolysis integrated system as a process step to produce power, heat and energy carriers

Laurens, Santiago (Matrikel Nr. 2141311)

Supervisors:

M. Sc. Tobias Zimmer (KIT)

Examiner:

Prof. Dr.-Ing. Martin Gabi

Dra. Ing. Cecilia Smoglie

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Declaration

I declare that I have developed and written the enclosed Master Thesis completely by myself and have not used any sources or means without declaration in the text. All thoughts from others and literal quotations are clearly marked. The Master Thesis was not used in the same or in a similar version to achieve an academic grading nor to be published elsewhere.

Karlsruhe, 21.05.2019

Place, Date

Laurens Santiago

Abstract

The growing concern about the increase in greenhouse gases and the consequences of these reached the point of having to resort to new and innovative technologies. In order to ensure the sustainable development of these technologies, a technical and economic pre-feasibility study is necessary to guarantee the successful development of these alternatives. The aim of this work is to provide a complete technical-economic evaluation of an integrated system of intermediate pyrolysis as a previous step of the process to produce energy, heat and energy carriers. This study will be based on 2 different systems: Pyro-CHP and Pyro-Micro biogas turbine. Both plants will be fed with waste from forestry and agriculture. The overall efficiency obtained for the Pyro-CHP system was in the range of 50-60% taking into account output heat and energy compared to the energy content of the feedstock. As for the Pyro-Micro pyrolysis gas turbine plant the overall efficiency obtained taking into account the electricity and the energy content of the products compared to the energy content of the feedstock, was around 60%. Using well known economic tools the capital investment required for a Pyro-CHP plant with a capacity of 25.000 tones per year was estimated to be € 24,5 million while a Pyro-Micro biogas turbine plant of the same size cost € 22,7 million. The levelized cost of energy obtained from the Pyro-CHP plant was 0,915 €/kWh in average, while Pyro-Micro biogas turbine plants around 0,25 €/kWh. Both results are not competitive as they are above market price. For the project to become viable scaling up the plants appears a good solution to reduce energy production costs. In order to maximize profits engineers should endeavour to find ways to reduce critical factors that most affect the profitability of the project. Factors such as capital investment, interest rate, energy and heat productivity, biodiesel price should be considered when minimizing the plant costs.

Kurzfassung

Die wachsende Besorgnis über den Anstieg der Treibhausgase und deren Folgen hat dazu geführt, dass auf neue und innovative Technologien zurückgegriffen werden muss. Um die nachhaltige Entwicklung dieser Technologien zu gewährleisten, ist eine technische und wirtschaftliche Vorstudie erforderlich, um die erfolgreiche Entwicklung dieser Alternativen zu gewährleisten. Ziel dieser Arbeit ist es, eine vollständige technisch-wirtschaftliche Bewertung eines integrierten Systems der Zwischenpyrolyse als vorhergehenden Schritt des Prozesses zur Herstellung von Energie, Wärme und Energieträgern durchzuführen. Diese Studie wird auf 2 verschiedenen Systemen basieren: Pyro-KWK und Pyro-Mikro-Biogasanlage. Beide Werke werden mit Abfällen aus der Forst- und Landwirtschaft versorgt. Der Gesamtwirkungsgrad des Pyro-KWK-Systems lag unter Berücksichtigung der Ausgangswärme und -energie im Vergleich zum Energiegehalt des Ausgangsmaterials im Bereich von 50-60%. Wie bei der Biogasturbinenanlage Pyro-Micro betrug der Gesamtwirkungsgrad unter Berücksichtigung des Stroms und des Energiegehalts der Produkte im Vergleich zum Energiegehalt des Ausgangsmaterials rund 60%. Mit Hilfe bekannter wirtschaftlicher Instrumente wurde der Investitionsbedarf für eine Pyro-KWK-Anlage mit einer Kapazität von 25.000 Tonnen pro Jahr auf 24,5 Mio. € geschätzt, während eine Pyro-Micro-Biogasanlage gleicher Größe 22,7 Mio. € kostete. Die nivellierten Energiekosten der Pyro-KWK-Anlage betrugen durchschnittlich 0,915 €/kWh, während die Pyro-Micro-Biogasanlagen rund 0,25 €/kWh betrugen. Beide Ergebnisse sind nicht wettbewerbsfähig, da sie über dem Marktpreis liegen. Damit das Projekt rentabel wird, erscheint die Skalierung der Anlagen eine gute Lösung zur Senkung der Energieerzeugungskosten. Um die Gewinne zu maximieren, sollten sich die Ingenieure bemühen, Wege zu finden, kritische Faktoren zu reduzieren, die die Rentabilität des Projekts am meisten beeinflussen. Faktoren wie Kapitalinvestition, Zinssatz, Energie- und Wärme energetische Efficienz, Biodieselpreis sollten bei der Minimierung der Anlagenkosten berücksichtigt werden.

Abstracto

La creciente preocupación por el aumento de los gases de efecto invernadero y sus consecuencias ha llegado al punto de tener que recurrir a tecnologías nuevas e innovadoras. Para asegurar el desarrollo sostenible de estas tecnologías, es necesario un estudio de prefactibilidad técnico y económico que garantice el desarrollo exitoso de estas alternativas. El objetivo de este trabajo es proporcionar una evaluación técnico-económica completa de un sistema integrado de pirólisis intermedia como paso previo al proceso de producción de energía, calor y carriers de energía. Este estudio se basará en dos sistemas diferentes: Pyro-CHP y Pyro-Micro biogas turbine. Ambas plantas se alimentarán con residuos de la actividad forestal y agricola. La eficiencia global obtenida para el sistema Pyro-CHP fue del orden del 55%, teniendo en cuenta como outputs el calor y la energía generada en comparación con el contenido energético de la biomasa usada como materia prima. En cuanto a la planta de turbina de biogás Pyro-Micro, la eficiencia global obtenida teniendo en cuenta la energía producida y el contenido energético de los productos en comparación con el contenido energético de la materia prima, fue de alrededor del 60%. Utilizando herramientas económicas ya establecidas, la inversión de capital estimada para una planta Pyro-CHP con una capacidad de 25.000 toneladas al año se estimó en 24,5 millones de euros, mientras que una planta de turbina de biogás Pyro-Micro del mismo tamaño costó 22,7 millones de euros. El coste medio de la energía obtenida de la planta Pyro-CHP fue de 0,915 €/kWh, mientras que el de las plantas de biogás de Pyro-Micro fue de unos 0,25 €/kWh. Ambos resultados no son competitivos, ya que están por encima del precio de mercado. Para que el proyecto sea viable, la ampliación de las plantas parece ser una buena solución para reducir los costes de producción de energía. Con el fin de maximizar las ganancias, los ingenieros deben esforzarse por encontrar formas de reducir los factores críticos que más afectan la rentabilidad del proyecto. Factores como la inversión de capital, la tasa de interés, la produccion de energia y calor y el precio del biodiésel deben tenerse en cuenta a la hora de minimizar los costes de la planta.

Nomenclature

EO = Evergreen Oak

VS = Vine Shoots

NS = Neem Seed

SS = Soya bean straw

BS = Barley Straw

PW = Pine wood

LHV = Low Heating Value

HHV = High Heating Value

EC = Equipment Cost

DPC = Direct Plant Cost

IPC = Indirect Plant Cost

TPC = Total Plant Cost

IRR = Internal Rata of Return

LCOE = Levelized Cost of Electricity

NVP = Net Present Value

IP = Intermediate Pyrolysis

R = Subsidy

$Cp_{biomass}$ = Specific Heat Capacity

TCR = Thermal Catalytic Reaction

Biogas = this term refers to pyrolysis gas

In this thesis the commas (,) will be used to separate the whole part of a number from its decimal part. The points (.) Will be used to separate the entire part between hundreds, thousands and millions.

INDICE

1 Introduction

1.1 Background

The increasing awareness on global warming, due to the growth of the earth means temperatures, as shown in figure 1, has become one of the main worldwide discussion. The growing number of natural disasters occurring every year, calls for innovative and new techniques, such as the biobattery concept (Trinks, Apfelbacher, Weger, Reil, & Hornung) to reduce the environmental impact of human activities by using natural resources more efficiently and in a responsible way.

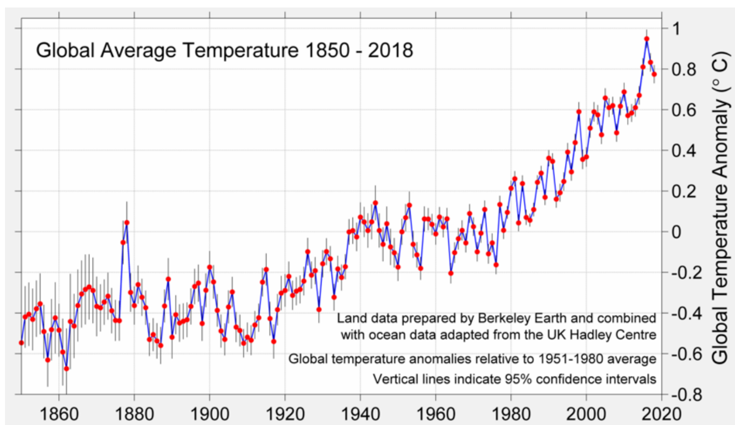

Fig. 1. *Annual average temperature between 1850 and 2018.*
Source: (Berkeley Earth Org., 2018)

The main reason for global warming is the increase in man-made greenhouse gas emissions, mainly CO_2 emissions (WIKIPEDIA, 2010). Figure 2 shows how CO_2 emissions have been increasing during the last years (IEA, 2018).

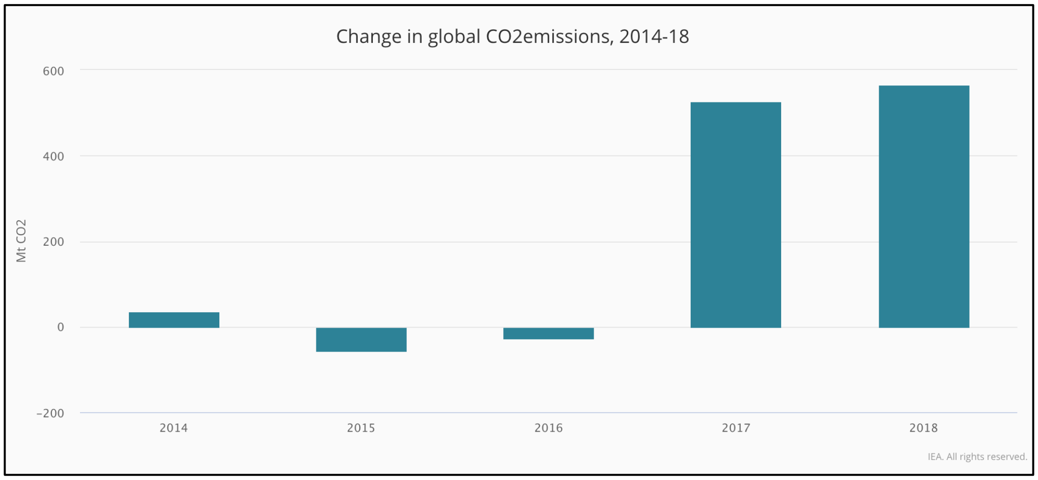

Fig. 2. *Annual greenhouse emissions . Source:*
https://www.iea.org/geco/emissions/

Emissions are produced by the different activities of men. The following graph, figure 3 shows the percentage distribution of the emissions according to the activity. As it can be observed, the production of energy, transport, burning biomass, agricultural activity and industrial processes represent the activities that produce the greatest amount of greenhouse gases.

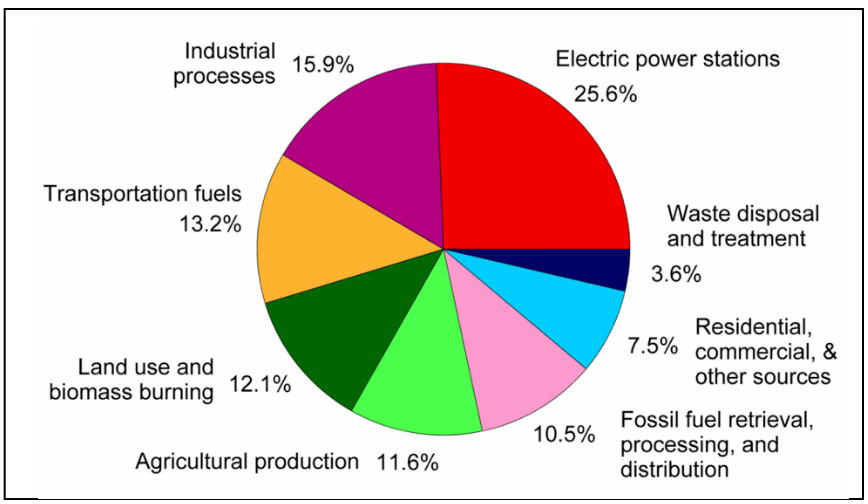

Fig. 3. *Annual greenhouse emissions by sector. Source:*
(WIKIPEDIA, 2010)

Furthermore, with the energy demand constantly increasing (IEA, 2019), as shown in figure 4, the future amount of emissions will tend to increase.

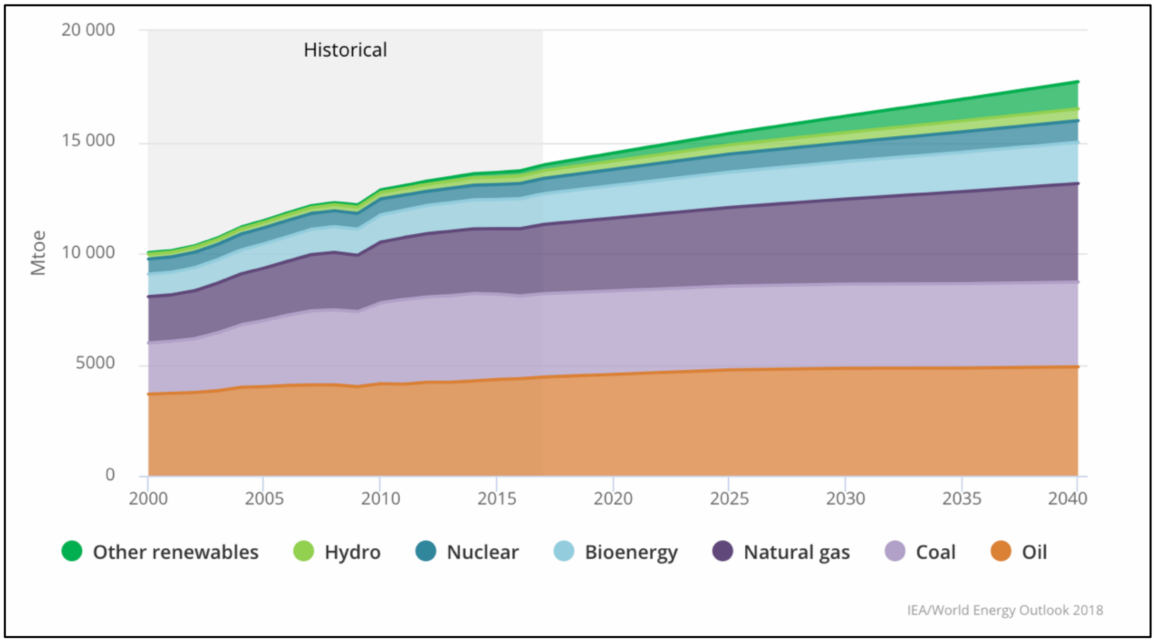

Fig. 4. *Total world primary energy demand. Source:* (IEA, 2019)

In order to reduce natural catastrophes due to global warming, 195 countries signed in Paris an agreement in 2015 in which they agreed on a long-term goal: keep the increase in global average temperature to well below 2 °C above pre-industrial levels; and to limit the increase to 1.5 °C (Wikipedia, 2015).

So as to reduce emissions and mitigate the greenhouse gases effect the concept known as Circular Economy is introduced. This model focuses on reducing to the minimum the waste and emissions of human activity (Morgano Tomasi, Bergfeldt, Leibold, Ritcher, & Stapf, 2018). Furthermore, this idea also implies the efficient use of local resources to reduce transport cost and emissions. In order to do this, secondary raw materials, emissions and waste from local human activity can be transformed into valuable resources such as valuable products, energy or even be part of a new process.

More than 10% of total world´s primary energy supply comes from biomass sources (Yang Y. , et al., 2017) . This denotes the importance of biomass as a renewable energy source and contributes to reduce the use of fossil fuels. In Argentina biomass sources supply 6,1% of the primary energy (Secretaria de Energia, 2017) while in Chile provides 61,79% of the primary energy (Ministerio de Energia, 2017).

There are many advantages that can be mentioned from the use of biomass as an energy source (Yang Y. , et al., 2017):

- Abundant: widely available
- Predictable in the short-middle term
- Carbon Neutral: can fixed carbon from the atmosphere

The possibility of applying thermal process (pyrolysis and gasification) to biomass in order to convert it to liquid and gaseous biofuels has been taken into account by scientist as well as for industrial commercialization for many years (Yang Y. , et al., 2017). Pyrolysis consist in the thermal decomposition of organic matter in the absence of oxygen and at elevated temperatures, in a range of 450 °C to 700°C. In this process 3 different products are obtained: pyrolysis oil, biogases and biochar which have the potential to be used combined to produce heat and power.

The integration of CHP units and pyrolysis in one process has become an efficient and effective solution to produce power and heat by the use of waste produced by agricultural activities. The results shows that this arrangement between the 2 processes improve CHP´s energetic and environmental performance (Kohl, P., & Järvinen, 2014).

Research carried out has shown promising results for this value chain. Yang (Yang Y. , et al., 2017) has concluded that and intermediate pyrolysis integrated with a diesel CHP unit reached a global efficiency of 42,5% using wood as biomass. Other study (Yang, Wang, Chong, & Bridgwater, 2018) obtained a global efficiency of 59,7%.

1.2 Motivation

In Argentina, only in Buenos Aires province during the campaign 2017/2018, agricultural production reached 38 million tonnes (Secretaria de Agroindustria, 2017/2018). 80% of this production correspond to wheat, soya and corn and left approximately 18,25 million tonnes of agricultural waste which were not used. The main residues of this agriculture products are the straw, stubble or stover.

In Chile, in the region of Araucania 190.000 tonnes of wheat straw residue was produced during 2010/2011 campaign (Roman-Figueroa, Montenegro, & Peneque, 2017) . Moreover, according to Roman-Figueroa (Roman-Figueroa, Montenegro, & Peneque, 2017) this region has the potential to produce 3,17 and 4,89 MWel with a 5 MWth plant using C/ST (fluidized bed combustion and generating turbine) or G/CC (fluidized bed gasifiers followed by a combined cycle of gas and steam) based on agriculture waste.

Intensive farming is consider to be one of the main activities causing the raise of greenhouse gases concentration in the atmosphere (Morgano Tomasi, Bergfeldt, Leibold, Ritcher, & Stapf, 2018).Integrating an intermediate pyrolysis process using agriculture waste to an energy system to produce energy and heat seems to be an attractive way to reduce greenhouse emissions and mitigate global warming effects. Furthermore, it can also be an efficient way to produce decentralized electric energy and respond to the constant increasing demand of energy.

By the integration of these two processes, an efficient use of the residues is made and electric energy and heat are produced which can be sold to the local grid or integrated in any industrial process. Costs in transport are reduced, as electricity is produced in a decentralized way.

The goal of this master thesis is to analyse, comprehend and understand an energy system integrated by an intermediate pyrolysis process with CP. This innovative energy system requires a global view of its efficiency, as well as its environmental impact and analysis of its economic variables. In order to achieve this, an analysis of different configurations and scale plants will be examined to ensure that the investment meets the goals set.

Following previous works, this thesis will, on the one side, evaluate different theoretical models using experimental information from prototype plants and, on the other side, simulate some parts of the process in Aspen Plus simulator in order to compare efficiencies and evaluate their impact in the global yield of the integrated system.

A theoretical model will be developed on a spreadsheet with different parameters that can be selected in order to evaluate their changes.

Finally, the purpose of this work consists of analysing the performance of the systems and its results to use it in a comprehensive and economic evaluation for calculating the levelized electricity cost which is the parameter that permits the comparison of different technologies. Additionally, a sensitive analysis of the factors that affect the levelized cost of electricity will be studied to examine the impact of the fluctuation of these variables.

1.3 Biomass description

The biomass can be classified according to (Dupont, Chiriac, Gauthier, & Toche, Heat capacity measurements of various biomass types and pyrolysis residues, 2013) in:

1. Wood: beech, angelim, faveira, macaßaranduba, hazelwood, pine, mixture Scot pine + spruce, poplar, vine shots, neem seed, evergreen oak.
2. Perennial crops: Miscanthus, switchgrass.
3. Agricultural by-products: wheat straw, rice husk, olive pomace, corn stover, barley straw, soybean straw.
4. Energy crops: triticale, tall fescue.

Taking into account the species that are cultivated in Buenos Aires province and in the Araucania region, this thesis will consider for the intermediate pyrolysis process only wood and agricultural by-products since they represent the main type of agricultural waste found in the selected locations.

Argentina is a country with a strong agricultural activity. Agricultural activity represents one of the main activity of its economy, especially in Buenos Aires, due to its great territory extension (126.126,42 km^2 of cultivate territory in the campaign 2017/2018) and its fertile soil and climate conditions (Secretaria de Agroindustria, 2017/2018). Total production in 2017/2018 campaign was 38.555.467 tonnes. Forest activity is less important, representing just the 5% in the agricultural activity (Secretaria de Agroindustria, 2018). The total production in 2016 was 600.000 tonnes mainly of Salicaceae, eucalyptus and pines.

Figure 5. Buenos Aires province*. Source:* (WIKIPEDIA, s.f.)

Chile, on the other hand, has a lower agricultural activity. In the case of the region of Araucania, during 2012/2013 agricultural season 105.500 ha of wheat were sown, corresponding to almost 45% of the total area sown in the country. Production reached 578.000 tonnes. Regarding the forest activity, there are 360.000 hectare designated to this activity (Gobierno regional de la Araucania, s.f.). The main species are Araucaria, Cypresses, oak and coigue (Ministerio de Agricultura - Chile, s.f.).

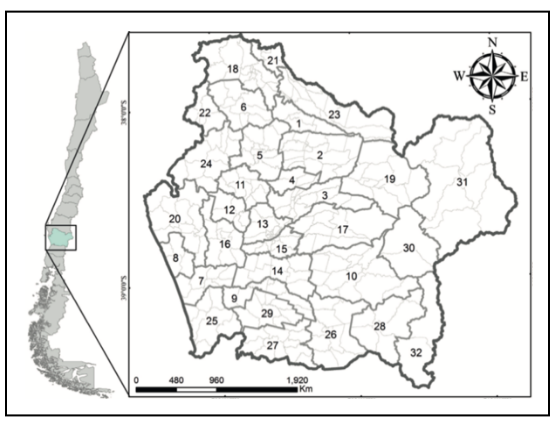

Figure 6. Araucanian region*. Source:* (Roman-Figueroa, Montenegro, & Peneque, 2017)

As the intermediate pyrolysis process is in a prototype stage there are no experiments carried out with Argentinian or Chilean biomass. In this study 3 different experiments: (Jäger, et al., 2016), (Tinwala, Mohanty, Snehal, Patel, & Pant, 2015) and (Yang Y. , Brammer, Mahmood, & Hornung, 2014) were used as a source of information for the intermediate pyrolysis. Since the experiments use many samples of different biomasses, they were divided into two categories according to their elementary composition: agricultural by-products and wood. Furthermore, from each experiment that was held at different temperatures, there was a selection of one kind of biomass in a way that it can be compared to Argentinian or Chilean biomass.

1.3.1 Intermediate Pyrolysis Process

Pyrolysis processes are an innovative technology to transform biomass into solid, liquid and gaseous products which in the future will be able to replace part of fossil fuels. According to (Mandal & Naidu, 2016) pyrolysis can be defined as the process in which organic matter is thermochemically decomposed into non condensable gases, condensable liquids, and a solid residual coproduct, biochar or charcoal. This process takes part in an inert environment, this means in the absence of oxygen. As it is shown in the next figure 7, intermediate pyrolysis is a process occurring in a range of temperatures of 500°C and 700 °C, approximately.

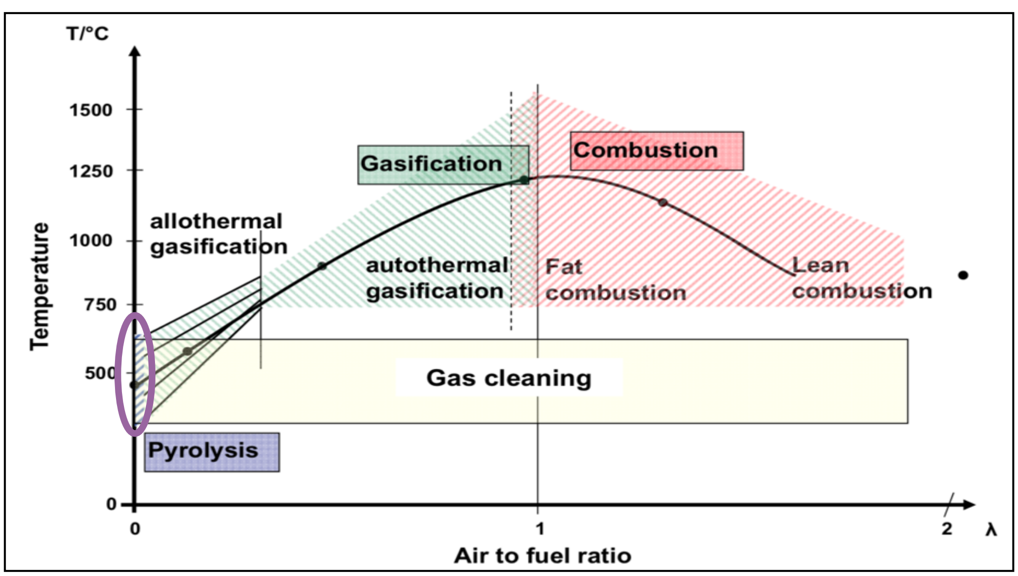

Figure 7. High temperature processes.*Source:* (Dahmen & Siegfried, 2019)

The main variables that control the process are temperature and residence time. By controlling this parameters the yield of the process can be optimized. Dependence of residence time and temperature can be seen in the next figures 8 and 9:

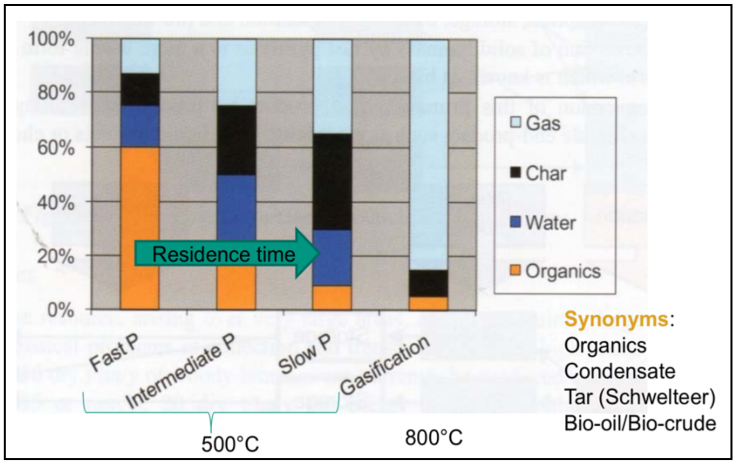

Figure 8. Residence time dependence.*Source:* (Dahmen & Siegfried, 2019)

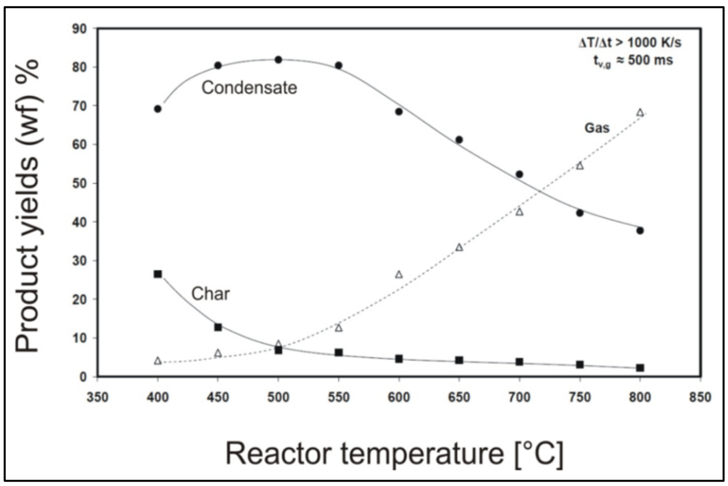

Figure 9. Temperature dependence.*Source:* (Scott, 1988)

As it is mentioned in (Dahmen & Siegfried, 2019) the most determining parameters in a pyrolysis process are the temperature and the residence time. By modifying this variables, the products that can be obtained are different. In the next figure 10, typical processes and yields are shown base on wood biomass.

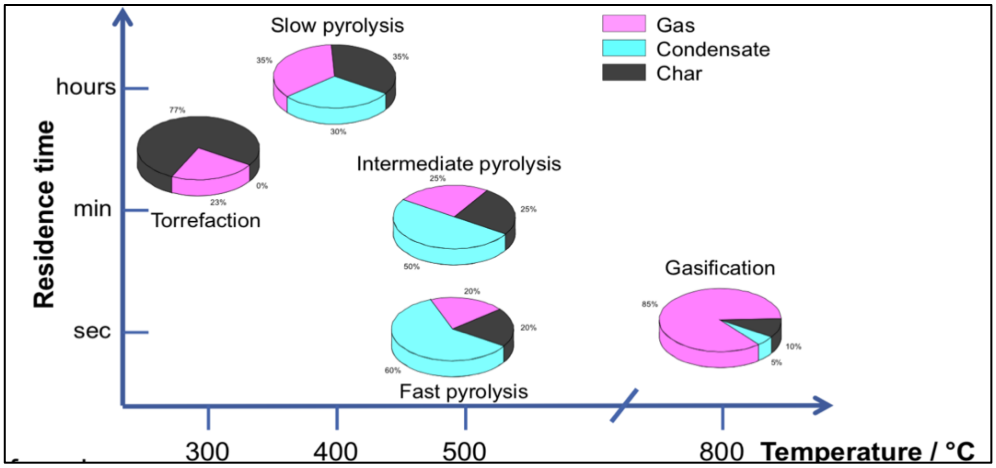

Figure 10. Different yields for different processes.*Source:* (Dahmen & Siegfried, 2019)

In this master thesis the focus will be put on an intermediate pyrolysis process. This process will be applied on different biomasses mentioned in the previous section.

Although the elementary composition of each biomass is different a chemical equation can be used to describe the pyrolysis of biomass and the products obtained (Dahmen & Siegfried, 2019):

$$C_6H_9O_5 \xrightarrow{\cong 500\,°C} C_2H + C_3H_5 + H_2O + CHO \quad (1)$$

In the next figure 11, there is a schematic representation of the intermediate pyrolysis process.

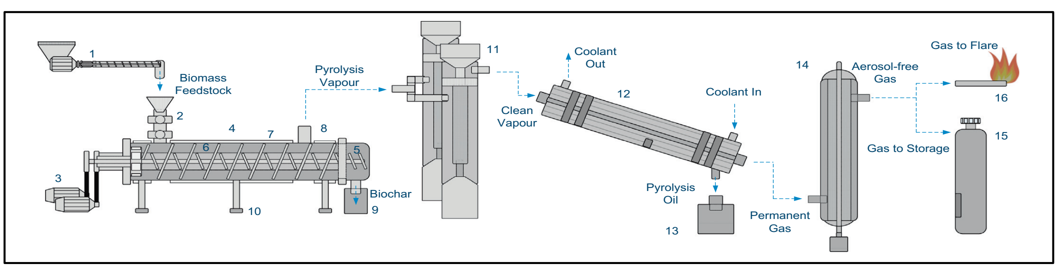

Figure 11. Schematic diagram of an intermediate pyrolysis system: (1) feeding system; (2) feed inlet; (3) electric motors; (4)pyrolysis reactor; (5) inner screw; (6) outer screw; (7) external heating jacket; (8) vapour outlet; (9)char pot; (10) stands; (11) hot gas filter; (12) shell and tubes condenser; (13) oil vessel; (14) electronic precipitator; (15) gass vessel; (16) gas flare . *Source:* (Yang Y. , Brammer, Mahmood, & Hornung, 2014)

2 Methodology

The integrated system is formed by three major subsystems: feedstock preparation (drying process), intermediate pyrolysis process and product separation, and, finally, engine generators. The model will evaluate two alternative processes which only differ in the treatment applied to the products, this means in the last subsystem. In this section both flowsheets will be shown to clarified this concept.

The system boundary entrance starts with the reception of the moist pellets of biomass and ends with the energy and heat production. The initial point of the model is the entry of received feedstock into the dryer. The final point of the model is the output of energy and heat form the generators.

In this chapter a description of the process model used for evaluating the different plants is going to be examined. The aim of this chapter is to:

- Show and describe the alternative integrated system using flowsheets
- Estimate energy and mass balance
- Stablish the boundaries of the integrated system as well as the scope of studies

A spreadsheet-based technical process was created to represent the process mass balance and the energy flow of each alternative. The global model was developed with single linked worksheets containing sub-models that related the overall process. A single parameter work-sheet allows to modify input variables to simulate different scenarios and obtain different results.

2.1 Feedstock preparation

The 6 types of feedstock evaluated in this work were agricultural waste obtained from forest and agricultural by-products activity. The biomass is supposed to be collected from local farmers.

The scope of this work does not involve the study of the mechanical treatment of the waste. Hence, it is considered that biomass is received in pellets with a regular size distribution and a moisture of 35%, as it was stablished in the previous chapter. The elementary composition will be described as well.

2.1.1 Drying process

During this process the biomass moisture percentage is reduced by the evaporation of water. The initial percentage in weight of biomass is assumed to be equal to all species and its value is 35%.

The biomass is dry till it reaches the initial moist used in the intermediate pyrolysis experiments. As information was taken from different studies, the output moisture differ between biomasses.

As regard the dryer, the cost and technical information was achieved from Peters (Peters, Timmerhaus, & West, 2003). The efficiency reference range of the dryer was adopted from the suggestion of this book, as well as the drummer model. As the analysis of this process does not represent one of the main aims of this thesis, some assumptions are done to simplify the model.

Assumptions:

1. Biomass initial moist: 35% for all samples
2. There is no loss of mass during the drying
3. Final moisture: the one stablish in the input feedstock of the intermediate pyrolysis (is not constant between the samples)
4. Initial temperature of the process: 25 ℃
5. Output temperature: 110 ℃
6. $Cp_{biomass}$ linear estimation according to (Dupont, Chiriac, Gauthier, & Toche, Heat capacity measurements of various biomass types and pyrolysis residues, 2013)
7. The balance is made per kilogram of wet biomass
8. Reactor efficiency range: 30 -70 %

2.1.2 Heat requirement for drying

The aim of this section is to estimate the size of the dryer and calculate its cost. In order to fulfil this task the heat needed for raising the temperature of the biomass and for evaporating the water in it, is calculated using the following equations:

$$Cp_{Biomass} = \%_{moist} Cp_{liquid\ water} + (1 - \%_{moist}) Cp_{feedstock} [KJ/Kg\ K] \quad (2)$$

$$\Delta H\ (Heat\ required) = Cp_{Biomass}(T_f - T_i) + \Delta H_{Vap} [KJ/Kg] \quad (3)$$

$\Delta H_{Vap}(latent\ heat\ of\ water) = 2450[KJ/Kg];\ Cp_{lw} = 4{,}19[KJ/Kg\ K];\ Cp_{Feedstock}$[1]$;\ \Delta T[K];$

The results can be seen in the next tables:

	Evergreen Oak (EO)	Barley Straw (BS)	Soybean Straw(SS)
Initial moisture (%)	35	35	35
Initial temperature (°C)	25	25	25
Final Moisture (%)	9,7	12,7	7,09
Final Temperature (°C)	110	110	110
Water remove (KG/KG)[2]	0,253	0,223	0,279
Heat (KJ/KG)[3]	862,5	797,4	913,9

Table 1. Agricultural by-products *dry analysis. Source: own made*

	Vine Shots (VS)	Pine Wood (PW)	Neem Seed (NS)
Initial moisture (%)	35	35	35
Initial temperature (°C)	25	25	25
Final Moisture (%)	10,7	11,7	12,8
Final Temperature (°C)	110	110	110
Water remove (KG/KG)[4]	0,243	0,233	0,222
Heat (KJ/KG)[5]	842,3	797,4	727,1

Table 2. Agricultural wood *dry analysis. Source: own made*

[1] (Dupont, Chiriac, Gauthier, & Toche, Heat capacity measurements of various biomass types and pyrolysis residues, 2013)

[24] KG H_2O/KG $_{wet\ biomass}$

[35] Heat per kilogram of wet biomass without dyer efficiency

After the examination of the results, the main difference is due to the difference of the final content of moist in the biomass.

2.2 Intermediate Pyrolysis

In this section, the main process of this thesis will be studied and analysed in detail. The primary input information of the pyrolysis process and its yields were based on pilot scale plants which have experimented with real biomasses.

Preceding related works (Tinwala, Mohanty, Snehal, Patel, & Pant, 2015), (Jäger, et al., 2016) and (Yang Y. , Brammer, Mahmood, & Hornung, 2014), were used for estimating the mass balance and the product composition and characteristics. In this papers the method applied is described for defining the properties of the pyrolysis products.

2.2.1 Experiment preparation

As it was mentioned, the intermediate pyrolysis process is in a prototype stage and there are no industrial plants available in the market. For example, figure 12 illustrates an example of the scale size of this experiments. In this section the experimental process will be described and it main variables, time and maximum temperature.

Figure 12. Experimental facility.
Source: (Yang Y. , et al., 2017)

The process begins with a conveyer belt to transport the feedstock and feeder that constantly supply the reactor.

The process continues then in the reactor where the thermos decomposition reaction takes place. Here, the feedstock is heated till the required temperature.

There are two types of reactor used for this process: screw reactor and fix bed reactor. Both reactors are characterized by providing indirect heat to the biomass, and they are characterized for providing significantly heating rate lower than fast pyrolysis and longer residence time.

The fix bed reactor (Tinwala, Mohanty, Snehal, Patel, & Pant, 2015), was used for the intermediate pyrolysis of NS and SS. For rising the temperature of the reactor, a ceramic band heater of 2 kW capacity was used, which provided a heat rate of 10°C/min. The maximum temperature reached was 500°C $\pm$ 10°C and the residence time was 10 minutes.

For the intermediate pyrolysis of EO, VS, W and BS a screw reactor was used, as it is shown in figure 11. This reactors operate thanks to an inner screw, moved by electric motors that provide the motion for the biomass. Meanwhile electric jackets, that are attached along the outer wall of the reactor, provide the needed heating to raise the mixture temperature to the required specifications. In the case of EO and VS, the temperature reached by the reactor was 700°C and the residence time 12 minutes. As for W and BS the maximum temperature was 600 °C.

Afterwards, at the end of the reactor, when the reaction has already occurred, char is collected at the end of the reactor in a pot and pyrolysis vapour leaves the reactor and passed through a filter that removes solid particles from the hot vapour. Next, the filtrated vapour is condensed in a heat exchanger to produce pyrolysis oil and biogas. Finally, the biogas is cleaned in an electrostatic precipitator.

2.2.2 Feedstock characterization

The input for the intermediate pyrolysis process is the output biomass from the dryer. The moist content vary in a range between 7,9% to 12,8%.

Assumptions used in this section:

1. Initial moisture: the percentage establish in the literature source
2. There is no loss of mass during the process
3. The methods used for composition analysis are presented in (Jäger, et al., 2016), (Yang Y. , Brammer, Mahmood, & Hornung, 2014) and (Tinwala, Mohanty, Snehal, Patel, & Pant, 2015)

Element(% weight)	**Evergreen Oak (EO)**	**Barley Straw (BS)**	**Soybean Straw(SS)**
C	0,44	0,44	0,43
H	0,06	0,06	0,06
N	0,01	0,00	0,01
S	0,00	0,01	0,00
O	0,45	0,35	0,47
H2O	0,10	0,16	0,04
HHV (MJ/Kg)	19,6	17,7	16,74
LHV (MJ/Kg)	16,77	17,5	16
Moisture (%)	9,7	12,7	7,09
Pyrolysis Temp.(℃)	690	600	500
Size(DxL)[6]	6 x 10-25	6 x 15-25	5-6 x 30-40
Source	(Jäger, et al., 2016)	(Yang Y. , Brammer, Mahmood, & Hornung, 2014)	(Tinwala, Mohanty, Snehal, Patel, & Pant, 2015)

Table 3. Agricultural by-products *feedstock characterization on a dry basis.*

[6] (Diameter x Length) mm

Element(% weight)	Vine Shots (VS)	Pine Wood (PW)	Neem Seed (NS)
C	0,48	0,48	0,48
H	0,06	0,05	0,07
N	0,01	0,00	0,02
S	0,00	0,00	0,00
O	0,41	0,36	0,35
H2O	0,08	0,07	0,07
HHV (MJ/Kg)	19,2	18,2	21,1
LHV (MJ/Kg)	18,37	17,84	20,5
Moisture (%)	10,7	11,7	12,8
Pyrolysis Temp.(℃)	690	600	500
Size(DxL)[7]	6 x 10-25	6 x 15-25	5-6 x 30-40
Source	(Jäger, et al., 2016)	(Yang Y. , Brammer, Mahmood, & Hornung, 2014)	(Tinwala, Mohanty, Snehal, Patel, & Pant, 2015)

Table 4. Agricultural wood *feedstock characterization on a dry basis.*

The low heating value was calculated using the HHV and the next equation (Channiwala) (Dahmen & Siegfried, 2019):

$$LHV = 34\, w(C) + 101{,}2\, w(H) + 6{,}3w(N) + 19{,}2w(S) - 9{,}8(O) - 2{,}5w(H2O) \qquad (4)$$

w(C),w(H),w(N),w(S),w(O),w(H2O) correspond to elements mass fraction

2.2.3 Pyrolysis Reaction

For calculating the heating required some assumptions are taken:

1. The heat of the reaction $\Delta_r H$ is completely contained in the reaction products as sensible heat.
2. Thermal losses will be calculated using the efficiency of the reactor.
3. Heat transfer rate will not be consider in this analysis.
4. The heat of reaction is equivalent to:

$$\Delta_r H = \sum \Delta_r H_i = \sum \Delta_f H_{products} - \sum \Delta_f H_{Educts} \qquad (5)$$

[7] (Diameter x Length) mm

$$\Delta_r H = \sum C_p \, \Delta T \qquad (6)$$

$$\Delta T = (T_{Int.Pyrolysis} - T_{dryer-out})°C;\ C_p = spedific\ heat\ capacity\ KJ/KgK$$

5. Heat capacity Cp: was estimated using (Dupont, Chiriac, Gauthier, & Toche, Heat capacity measurements of various biomass types and pyrolysis residues, 2013). Linear approximation was used to calculate the heating values in the interest range of temperature. Cp is assumed to be constant in the studied range of temperature (Figure 13).
6. Pression in the reactor is assumed as standard.
7. Yields were obtained experimentally. Mass conservation is assumed.

2.2.3.1 Heat Capacity

In the investigated range of temperatures the behaviour of heat capacity was considered linear, for wood as well as agricultural by-products. This estimation can be seen in the next figures 13 and 14:

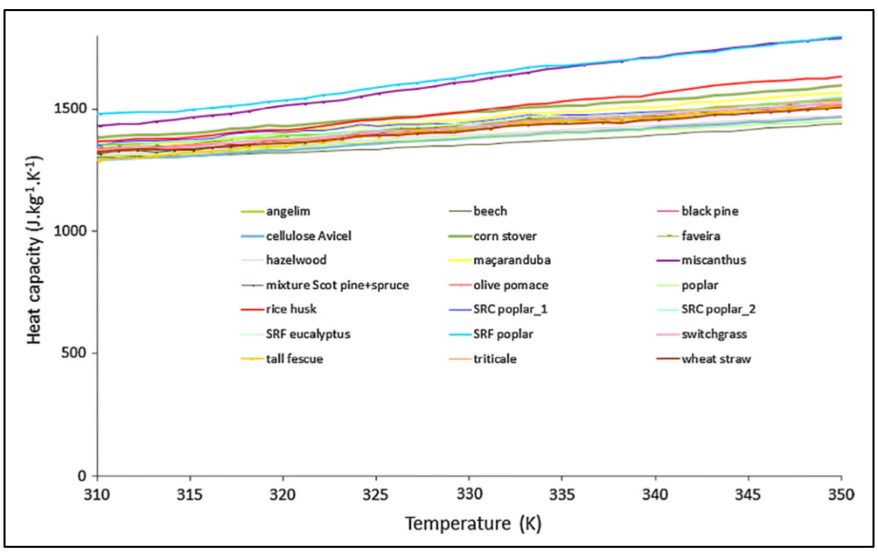

Figure 13. Heat capacity of biomass samples.*Source:* (Dupont, Chiriac, Gauthier, & Toche, Heat capacity measurements of various biomass types and pyrolysis residues, 2013)

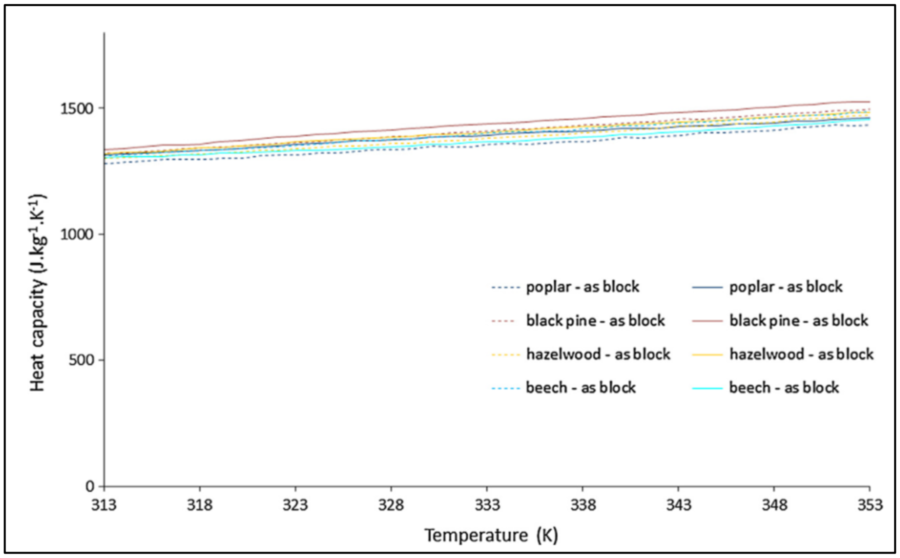

Figure 14. Heat capacity of various wood samples.*Source:* (Dupont, Chiriac, Gauthier, & Toche, Heat capacity measurements of various biomass types and pyrolysis residues, 2013)

In the next tables the estimated heat capacity of each biomass is shown. The calculation was done using Table 1 from (Dupont, Chiriac, Gauthier, & Toche, Table 1 - Heat capacity measurements of various biomass types and pyrolysis residues, 2013) and taking into account the content of moisture. The next equation was applied:

$$Cp_{Biomass} = \%_{moist} Cp_{liquid\ water} + (1 - \%_{moist}) Cp_{feedstock} \qquad (7)$$

	Evergreen Oak (EO)	Barley Straw (BS)	Soybean Straw(SS)
Heat Capacity (KJ/Kg.C)	3,68	3,27	2,75
Interpolation range (℃)	80-690	80-600	80-500

Table 5. Heat capacity of by-products *biomass. Source: own source*

	Vine Shots (VS)	Pine Wood (W)	Neem Seed (NS)
Heat Capacity (KJ/Kg.C)	3,69	3,25	2,84
Interpolation range (℃)	80-690	80-600	80-500

Table 6. Heat capacity of wood *biomass. Source: own source*

It must be noticed that values differ not only for the composition of each biomass but also because the interpolation temperatures are different as the intermediate pyrolysis was carried out at different temperatures. Furthermore, the lecturer must consider this is an estimation, and values can differ in reality. However, according to (Dupont, Chiriac, Gauthier, & Toche, Heat capacity measurements of various biomass types and pyrolysis residues, 2013) the influence of biomass type represent a variation up to 20%. Hence, an average linear correlation may be sufficient for describing heat capacities of all biomasses in thermal conversion models.

2.2.4 Products Characterization

The methods used for products analysis are presented in (Jäger, et al., 2016), (Yang Y. , Brammer, Mahmood, & Hornung, 2014) and (Tinwala, Mohanty, Snehal, Patel, & Pant, 2015).

Products		**Evergreen Oak (EO)**	**Barley Straw (BS)**	**Soybean Straw(SS)**
Char	**Yield (wt%)**	**25**	**44**	**40**
Element(wt%)	C	84,2	74,83	65,42
	H	1,2	3,51	1,41
	N	0,8	0,1	0,61
	S	0,1	-	0,07
	O	1,5	8,46	21,57
	Moisture	0,4	-	-
	Ash	12,2	-	-
Energy	HHV(MJ/Kg)	30,3	32,9	23,28
	LHV(MJ/Kg)	27,68	28,15	21,61
Bio-oil	**Yield(wt%)**	**7**	**29**	**35**
Element(wt%)	C	75,2	62,3	-
	H	7,4	8,12	-
	N	2,2	1,41	-
	S	0,3	-	-
	O	14,9	25,8	-
	Moisture	8,2	5,8	-
	Ash	0,05	0,1	-
Energy	HHV(MJ/Kg)	33,6	28,9	22,64
	LHV(MJ/Kg)	31,62	26,94	-
Biogas	**Yield(wt%)**	**68**	**27**	**25**
Element(wt%)	C_xH_y	2	-	34,9
	CO_2	25	60,13	7,8
	CH_4	11	10,48	18,53
	CO	14	21,74	13,85
	H_2	36	1,4	8,3
	O_2	-	0,42	10,6
	N_2	-	4,68	-
Energy	HHV(MJ/Kg)	14,75	10,55	-
	LHV(MJ/Kg)[8]	13,2	10,55	10,55

Table 7. Agricultural by-products *characterization. Source:* (Yang Y. , Brammer, Mahmood, & Hornung, 2014) (Tinwala, Mohanty, Snehal, Patel, & Pant, 2015) (Jäger, et al., 2016)

[8] [8] LHV (Yang Y. , Brammer, Mahmood, & Hornung, 2014)

Products		Vine Shots (VS)	Pine Wood (W)	Neem Seed (NS)
Char	**Yield (wt%)**[9]	**27**	**27**	**29**
Element(wt%)	C	70,8	75,6	68,83
	H	1	3,38	2,53
	N	0,9	0,22	1,77
	S	0,1	-	0,11
	O	0,7	10,2	13,29
	Moisture	0,6	10,6	-
	Ash	23	-	-
Energy	HHV(MJ/Kg)	25,5	30,1	25,84
	LHV(MJ/Kg)	25,08	28,15	22,39
Bio-oil	**Yield(wt%)**	**8**	**17**	**44**
Element(wt%)	C	78,6	55,69	-
	H	7,2	7,93	-
	N	2,5	0,36	-
	S	0,3	-	-
	O	11,4	36,02	-
	Moisture	8,4	15,4	-
	Ash	0,05	0,18	-
Energy	HHV(MJ/Kg)	35,5	24,2	25,68
	LHV(MJ/Kg)	32,9	23,09	-
Biogas	**Yield(wt%)**	**65**	**56**	**27**
Element(wt%)	C_xH_y	1	-	44,8
	CO_2	27	50,27	7,16
	CH_4	12	7,24	15,87
	CO	13	35,7	0,46
	H_2	35	2,24	6,89
	O_2	-	-	18,46
	N_2	-	5,54	-
Energy	HHV(MJ/Kg)	14,75	11,1	-
	LHV(MJ/Kg)[10]	13,27	10,55	10,55

Table 9. Wood products *characterization. Source:* (Yang Y. , Brammer, Mahmood, & Hornung, 2014) (Tinwala, Mohanty, Snehal, Patel, & Pant, 2015) (Jäger, et al., 2016)

[9] Product distribution
[10] [10] LHV (Yang Y. , Brammer, Mahmood, & Hornung, 2014)

2.2.4.1 Mass balance

Figure 15 summarises the composition of the intermediate pyrolysis products under different experiment conditions. The masses balances reveal irregular yields. The cause of this is not only the experiment physics conditions but also the elementary composition of each type of feedstock. Similarities can only be detected when comparing processes at the same pyrolysis temperature (EO-VS, BS-W, SS-NS). As expected, the highest biogas yield matches with highest pyrolysis temperature, in EO and VS biomasses. On the other side, analysis shows that the maximum yields of bio-oil, 44%, is founded in NS, corresponding to the lowest temperature of reaction.

In terms of the char, yields show a more regular behaviour, with values that fluctuate between 25% and 45%.

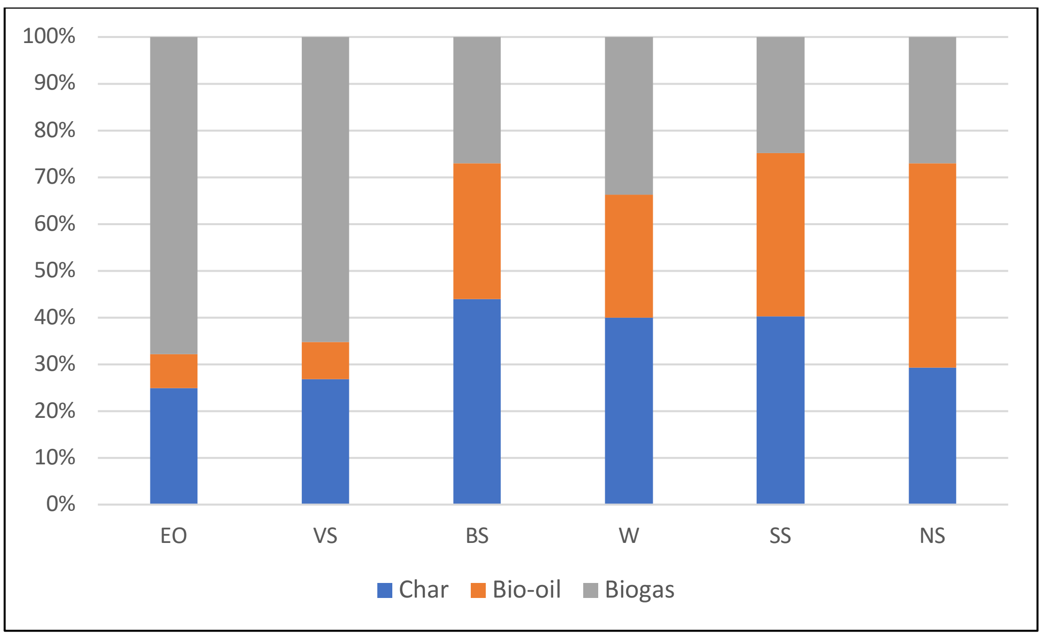

Figure 15. Mass balance of products for the different feedstock. *Source: own source*

As regard the comparison between agricultural by-products and wood biomass, the information used is not enough to make conclusions with enough certainty. Then again, there are many variables such as element composition, temperature, moist, time of residence, heat rate exchanged, just to mention some, that differ in each sample used and do not let make an affirmation about the behaviour of biomass.

2.2.4.2 Energy balance

The global energy balance was estimated taking into account the LHV and the mass balance of each product as it is shown in figure 16.

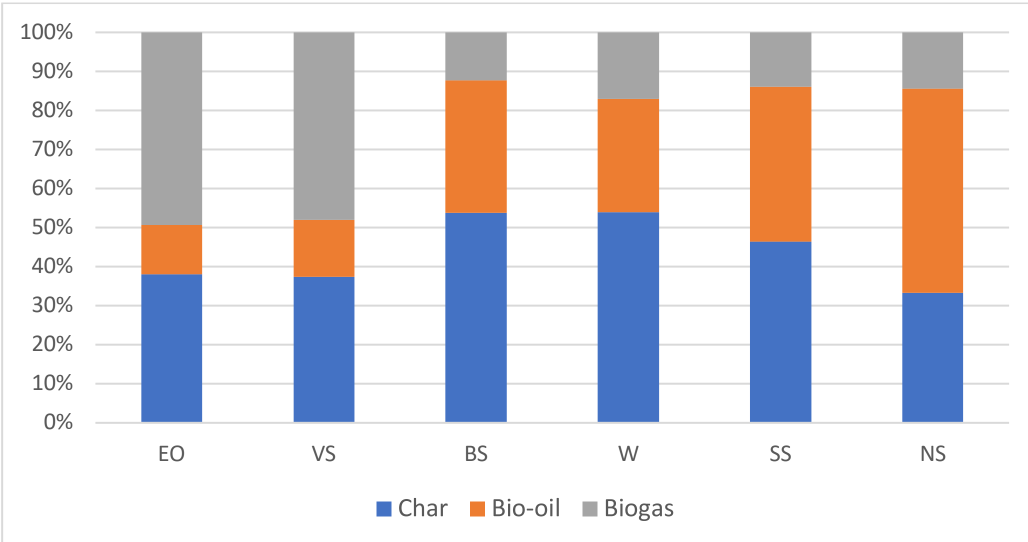

Figure 16. Energy balance of products*. Source: own source*

The energy balance revealed that the energy conversion differs on each species of biomass and depends on the LHV and on the mass balance. When analysing the graph it can be seen that the energy was mainly converted to char and biogas for reaction occurring at high temperature. For example EO shows a conversion of almost 90% in biogas and char energy if sum up together. In the case of reactions at lower temperature (SS-NS) energy was primarily converted to char and bio-oil, reaching approximately a value of 85% considering both products together.

2.3 Integrated system: power and heat generators

In this section, the third subsystem is going to be analysed. The integration to the dryer and pyrolysis reactor allow different configurations. Two alternatives are going to be studied and compared.

2.3.1 Alternative 1: Pyro- CHP units integration

As shown in figure 17, this integrated system begins with the reception of biomass. Afterwards, it is dried. Once, the moist content is reduced the biomass is sent to the intermediate pyrolysis reactor to produce char, biogas and bio-oil. The first product obtained, char, is burned in a combustor to deliver the heat required for the drying and pyrolysis process. The bio-oil is separated from the water (by density difference) and storage in an oil vessel. After, it is blended in a 50% mixture with biodiesel and burned in a diesel based CHP unit system. As regard the biogas, after it is cleaned it can be directly combusted in a gas engine CHP unit system.

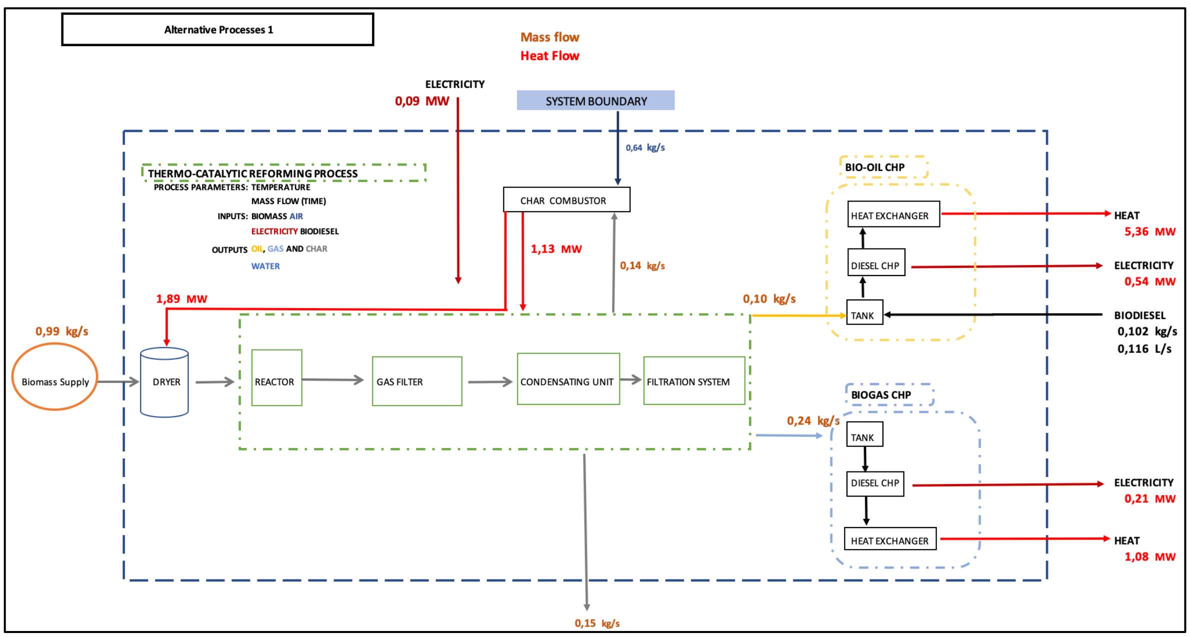

Figure 17. Pyro-CHP integrated system. *Source: own source*

2.3.1.1 Char combustion

The solid char is firstly storaged. Then, it is directly burned in a combustor at around 1252°C according to (Dahmen & Siegfried, 2019), to generate hot gases which will be used to provide the required heat for the dryer and the pyrolysis reactor. The temperature is calculated using the next equation:

$$C_6H_80_4 + 2.6(O_2 + 3.8N_2) \rightarrow 6CO_2 + 4H_2O + 6O_2 + 45.6N_2 \quad (8)$$

$$\Delta_r H = \sum \Delta_r H_i = 2871 \frac{Kj}{mol \rightarrow} = \sum Cp_i(T_f - 298) \quad (9)$$

$Cp_{O2} = 35,6\ [j/mol\ K]; Cp_{CO2} = 56,2\ [j/mol\ K]; Cp_{H2O} = 43,9[j/mol\ K]; Cp_{N2} = 33,7\ [j/mol\ K]$

$$T_f = 1252\ ℃$$

A controlled stream of the flu gas is pumped to both equipment so that they meet the temperature demands, 110℃ for the dryer and 500℃-690℃ for pyrolysis process (is not always the same). The unused char can be sold to the market.

2.3.1.2 Power and heat generation

The integrated system for providing heat and power consist of a diesel engine generator which uses as fuel biodiesel and bio-oil in the same proportions and a gas engine generator fully fuelled by biogas. The heat and power generated by both systems are sold to the grid and represent the incomes of the plant.

A dual system, bio-oil and biogas together, was not considered because a duel engine system is not yet a proven technology and because this system will imply a fixed ratio of bio-oil and biogas that is difficult to achieve as there is a width range of biomasses with different yields.

The electricity produced can be sold either to the company in charge of the distribution in Argentina or Chile or privately to a company and take advantage of the benefits of using renewable energy.

As for the heat, the hot gasses are used to heat water for supplying a local factory or the local district heating network. Although, there are not many local heating network infrastructure in both countries, it is assumed that it is installed and ready to be connected to the plant.

2.3.1.3 Global process: mass and energy balance

As it was mentioned, the global model shown in the schematic figure 17 was developed on a spread-sheet that calculates the mass and energy balance based on experimental work carried out in different facilities testing a wide range of biomasses.

The model has variables that can be modified in order to obtain different results. Parameters such as pyrolysis temperature, type of biomass, annual tonnes processed of biomass, equipment efficiencies and annual operation hours affect the mass balance and consequently the energy balance.

The energy requirement of the process are mainly the heat needed in the dryer and the reactor. This subsystem is the major energy consumer. The heat required is calculated using equation (3) for the dryer and equation (5) for the reactor. Both estimations are then increasingly affected by the efficiency of the equipment.

The CHP equipment used in this plants were selected from the (U.S. EPA-Partnership, 2007) catalogue. In this catalogue technical information such as dimensions, efficiencies and costs are provided. Although, the efficiencies of the equipments were stablished as a variable in the spreadsheet (as it may vary), reference efficiencies were stablished: for the biogas engine a thermal efficiency of 41% and 8% electric efficiency (U.S. EPA-Partnership, 2007); for the diesel engine a thermal efficiency of 59% and 6% electric efficiency (U.S. EPA-Partnership, 2007).

The global efficiency of the process was calculated taking into account the relationship between the total energy input from the feedstock, electricity demand, diesel energy content and the total energy output of electricity, heat and products.

$$\eta_{global} = \frac{P_{electric} + P_{heat}}{P_{feedstock} + P_{eletricity} + P_{diesel}} \tag{10}$$

2.3.2 Alternative 2: Pyro-Micro biogas turbine

As shown in figure 18, this integrated system begins the reception of biomass. Afterwards, it is dried. Once, the moist content is reduced the biomass is sent to the intermediate pyrolysis reactor to produce char, biogas and bio-oil. The obtained char and bio-oil are sold to the market. As regards the biogas, after it is cleaned it can be directly combusted in a gas engine unit. The flu gas from the combustion of the biogas (approximately 750 ℃) are recovered using a heat exchanger, the dryer and the reactor.

The main assumption in this configuration is to assume that the bio-oil and char can be sold in the market as bio-energy resources.

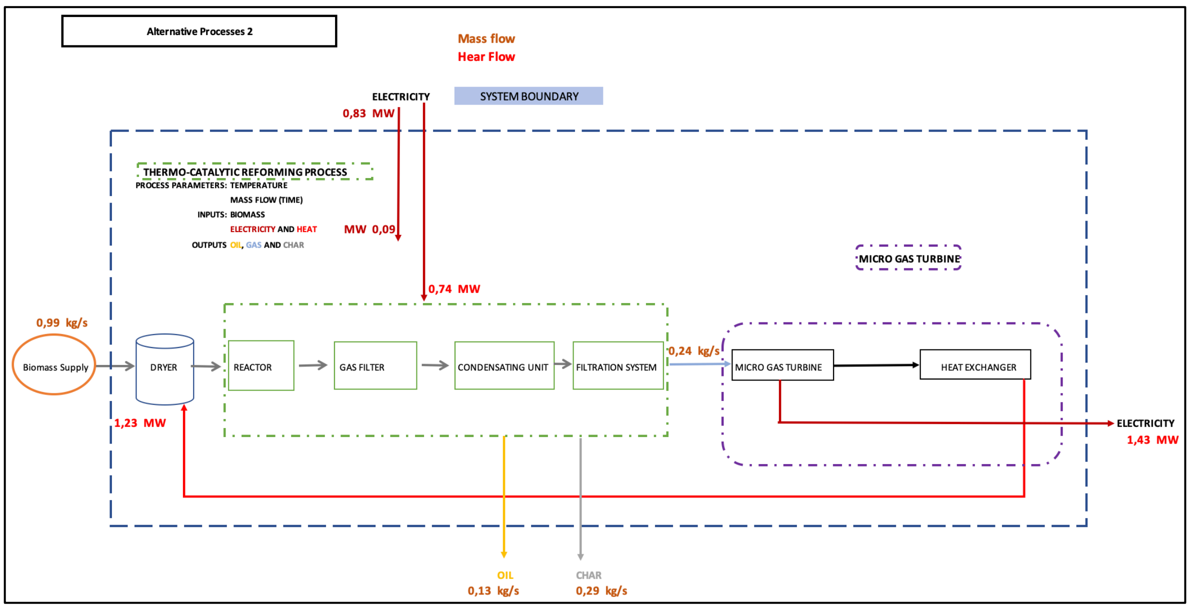

Figure 18. Pyro-CHP integrated system. *Source: own source*

2.3.2.1 Gas combustion

The biogas is combusted in a gas engine that is used to generate electricity. The estimated temperature varies depending the composition of the biogas. Hence, biomasses compositions are all different, therefore it is difficult to estimate (Dahmen & Siegfried, 2019) (VALERA-MEDINA, et al., 2018). Consequently, the temperature of the exit flu gas assumed was 750°C . This heat is recovered by a heat exchanger and used to dry the biomass.

As the heat is not enough for the whole process, the pyrolysis reactor is heated using electricity provided externally from the grid.

2.3.2.2 Power and heat generation

The integrated system for providing power comprehends a gas engine generator which uses as fuel the produced biogas.

The electricity produced can be sold either to the company in charge of the distribution in Argentina or Chile or privately to a company and take advantage of the benefits of using renewable energy.

Flu gas exiting the micro turbine is collected and passes through a heat exchange to use that heat to respond to the demands of the reactor and the dryer. In this case the heat recovered, using the efficiencies references from (Dr. Fromme International - Consulting, 2016), was not enough to respond to the demands.

Key Facts: Gas Engines	
Typical capacity range	1 kW_{el} – 10 MW_{el}
Electric efficiency	~ 35 – 45%
Typical costs	From > 1,000 €/kW for small scale to < 500 €/kW for MW size
Application focus	Broad application fields

Figure 19. Gas engine characteristics. *Source:* (Dr. Fromme International - Consulting, 2016)

2.3.2.3 Global process: mass and energy balance

As it was previously mentioned, the global model shown in the schematic figure 18 was developed on a spread-sheet that calculates the mass and energy balance based on experimental work carried out in different facilities testing a wide range of biomasses.

The model has variables that can be modified in order to obtain different results. Parameters such as pyrolysis temperature, type of biomass, annual tonnes processed of biomass, equipment efficiencies and annual operation hours affect the mass balance and consequently the energy balance.

The energy requirement of the process is mainly the heat needed in the dryer and the reactor. This subsystem is the major energy consumer. In this alternative system, external energy for the pyrolysis reactor is required.

The gas equipment used in this plants was selected from the catalogue (Dr. Fromme International - Consulting, 2016). In this catalogue technical information such as dimensions, efficiencies or cost are provided. Although, the efficiency of the equipment was stablished as a variable in the spreadsheet (as it may vary), reference efficiencies were stablished: for the biogas engine a thermal efficiency of 55% and 35% electric efficiency.

The global efficiency of the process was calculated taking into account the relationship between the total energy input from the feedstock and electricity demand and the total energy output of electricity and energy content in products.

$$\eta_{global} = \frac{P_{electricity} + P_{product}}{E_{feedstock} + P_{eletricity}} \qquad (11)$$

3 Aspen model

The aim of this chapter is to develop system models that simulate specific process routes for the thermochemical reactions of biomass and combustion of products using the processing simulation software provided by Aspen Plus. The main idea is to simulate the process in the spread sheet and in Aspen using the same input information. These will provide other results to compare the performance of different steps of the process. More specifically it will allow the comparison of efficiencies assumed in the spread sheet model. A dryer model and a combustor are created in Aspen Plus so to simulate this processes.

3.1 Dryer

The Dryer system model, shown in figure 20, consist of a contact dryer unit that reduce the moist content of the wet biomass to the required ones. The required input moist for the intermediate pyrolysis were stablish in section 2.1.2.

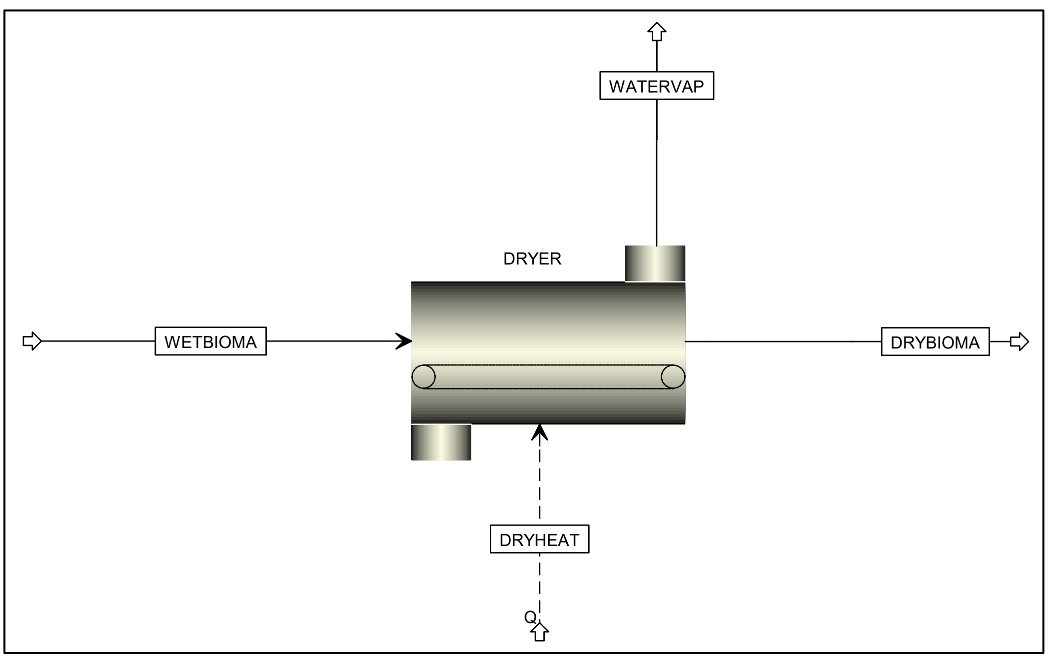

Figure 20. Aspen dryer model. *Source: own source*

3.1.1 Model inputs

In order to simulate the drying process the model required input information and making assumptions. Next, the requirement for the model will be listed:

1. Elementary composition of biomass (wt%) stablish in table 3 and 4
2. Wet biomass flow: 1 kg/s
3. Dryer length: 12 m
4. Initial moisture: 35% (wt)
5. Ash content: 9,2%
6. Size particles: 10%:120-140 μm; 20%:140-160 μm; 30%:160-180 μm; 40%:180-200 μm
7. Biomass: nonconventional type (heterogeneous solids that not participate in chemical equilibrium; the only properties that are calculated for nonconventional components are enthalpy and density
8. Method: ideal

In the next table 9, the results from the simulations are provided:

Biomass		**EO**	**VS**	**W**	**BS**	**NS**	**SS**
Spread-sheet model	Efficiency (%)	45	45	45	45	45	45
Aspen Plus model	Efficiency (%)	37	37	36	39	36	36
Variation	%	8	8	9	6	9	9

Table 9. *Efficiencies estimation. Source: own source*

The results reflect that according to Aspen Plus the efficiency is lower than the one assumed in the spread sheet. The average difference estimated was 8,24% with a standard deviation of $\pm$ 1,02%.

A lower drying efficiency will impact in the overall efficiency of the system and, of course, will affect the economic outcomes. This results will be studied and analysed in chapter 4, were they are evaluated in both systems.

3.2 Combustor

The Combustor system model, shown in figure 21, consists of different blocks units that together allow the stimulation of the combustion of dry coal (with the moist content establish in section. The required input moist for the intermediate pyrolysis were stablished in chapter 2, section 2.1

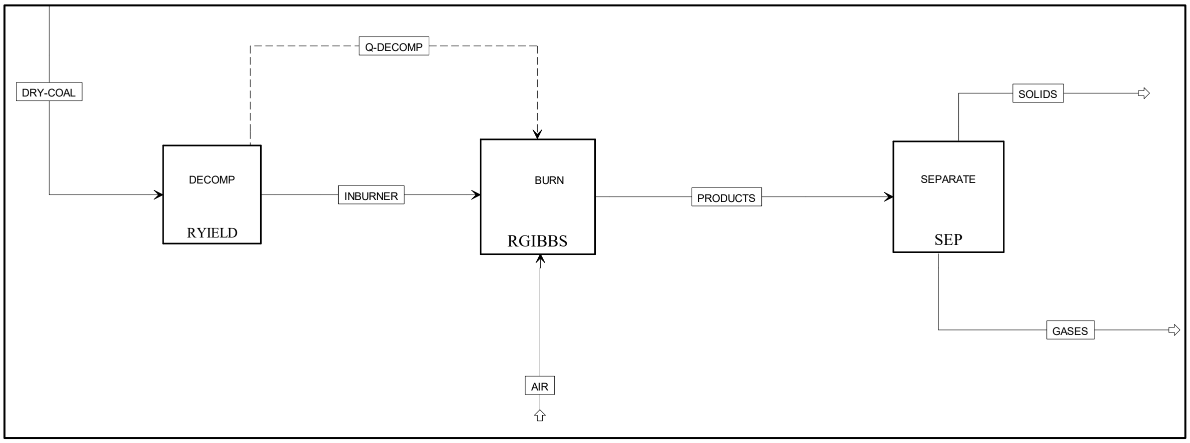

Figure 21. Aspen combustor model*. Source: own source*

3.2.1 Model inputs

In order to simulate the drying process the model required input information and making assumptions. Next the requirement for the model will be listed:

1. Elementary composition of biomass (wt%) stablish in table 3 and 4
2. Wet biomass flow: 1 kg/s
3. Moisture content: specified in section 2.2.1
4. Ash content: 9,2%
5. Size particles: 10%:120-140 μm; 20%:140-160 μm; 30%:160-180 μm; 40%:180-200 μm
6. Air = 79% N_2 and 21% O_2 (wt%)
7. Pressure: ambient pressure = 1 atm
8. Coal in the figure represent the biomass
9. RYield decompose dry coal into its constituent elements
10. Q-Decomp represent the heat required for the decomposition of coal

11. RGibbs reactor simulate the combustion of dry coal. This kind of reactor reach chemical equilibrium my minimizing Gibb free energy
12. Global stream: MCINCPSD

In the next table 22, the results from the simulations are provided:

Biomass		**EO**	**VS**	**W**	**BS**	**NS**	**SS**
Spread-sheet model	Efficiency (%)	45	45	45	45	45	45
Aspen Plus model	Efficiency (%)	37	37	36	39	36	36
Variation	%	8	8	9	6	9	9

Figure 22. Combustor efficiencies comparison*. Source: own source*

The results reflect that according to Aspen Plus the efficiency is lower than the one assumed in the spreadsheet. The mean average difference estimated was 8,24% with a standard deviation of $\pm$ 1,02%.

A lower combustor efficiency will impact in the overall efficiency of the system and of course will affect the economic outcomes. This results will be studied and analysed in the next chapter.

4 Economic evaluation

In this chapter the integrated system will be evaluated and compared from the economic point of view. The aim of this chapter is to obtain different values in order to compare the different alternative plants among each other and with other similar intermediate pyrolysis integrated system

4.1 Economic model

In this section the theoretical model will be described taking into account all the assumptions made.

4.1.1 General assumptions

The general assumptions made were based in similar works (Yang, Wang, Chong, & Bridgwater, 2018), (Yang Y. , et al., 2017) and (Trippe, Fröhling, Frank, Stahl, & Henrich, 2010), this means plants that used biomass to produce heat, power and bioenergy products.

The main assumptions considered were:

1. Project life: considering the lifetime of the main equipment and its amortization, the lifetime project was taken to be 20 years. The salvage value of the equipment at the end of the project is assumed to be 10%.
2. Operation hours: although it is a variable that can be modified in the spread-sheet model, considering maintenance (30 days per year) and availability (between 75% and 95%) the operations hours are in a range between 6030 and 7638 annually.
3. Interest rate: in the mentioned projects this value fluctuates between 7% and 15%. As reference 10% will be assumed although it is no fixed.
4. Location: it is assumed that the plant will be located in an area where the transport of agricultural waste is minimized and where electricity and heat can be sold, this means, there is infrastructure available for the plant to directly sell its products. It is also assumed that bioenergy products, such as char, biogas or bio-oil are sold to final consumers. As to mention possible locations for the plant, some suggestion could be near Temuco (around 0,5 million people) in Araucania region or the north

of Buenos Province which has many important cities such as San Nicolas, Pergamino, Ramallo and San Pedro.

4.1.2 Capital cost

In this study the capital necessary to install and start up the plant was estimated using as model the economic investigation established by Bridgwater et al. around the 2000s (Bridgwater, Toft, & J.G., 2002).

The aim of this section is to determine the total plant cost (TPC) which covers the overall capital investment needed to finance the integrated system till the point is ready to operate by itself. This cost of development and construction must be included.

The first step is to calculate the equipment cost (EC). This cost includes the purchase of the main new equipment that integrates the system and its delivery to the plant. The result of this prices includes[11] literature research and web catalogues suppliers.

As regards evaluating the scaled up systems, for costs that the literature or suppliers does not provide information of the scale-up cost, capacities are adjusted using the six-tenths rules, equation, cited by Sinnot (Sinnot, 2005) and SKM Enviros (Enviros, 2011).

$$C_B = C_A(\frac{S_B}{S_A})^{0,6} \tag{12}$$

$C_B = cost\ (\$) of\ equipment\ having\ size\ SB$

$C_A cost\ (\$) of\ equipment\ having\ size\ SA;$

$^{S_B}/_{S_A}\ s\ the\ ratio\ known\ as\ the\ size\ factor, dimensionless$

[11] (Peters, Timmerhaus, & West, 2003), (U.S. EPA-Partnership, 2007), (Matches, 2019), (S2Biom, 2019), (Dr. Fromme International - Consulting, 2016), (Peters, n.d.), (Engineers, 2016)

Once all the ECs are summed up, it is necessary to estimate direct plant cost (DPC) related to them. This is calculated by using incremental factors for each cost affecting the installation and set-up of the equipment.

Furthermore, it is also necessary to consider costs such as engineering and supervision or construction fees. These are indirect (plant) cost plant (IPC) and are also estimated using incremental factors.

Finally, but not less important, is the working capital cost. The working capital includes the cost needed to start operating the plant: raw materials and supplies carried in stock; finished products in stock and semi-finished products in the process of being manufactured; accounts receivable; cash kept on hand for monthly payment of operating expenses, such as salaries, wages, and raw material purchases; accounts payable; and taxes payable. According to (Peters, Timmerhaus, & West, 2003), the range of this value is between 10% and 20%.

As it is noticed, the estimation of the TPC has a great level of uncertainty, as it is based on an incremental factor that can take a wide range of values. In order to have a reference TPC value to compare results, incremental factor assumed by Trippe F. at (Trippe, Fröhling, Frank, Stahl, & Henrich, 2010), that are based on a fast pyrolysis plant, were taken as default and will be compared with random values obtained by simulating each factor in the range of interest. In the next table 10 there is a summary of the factors applied.

The annual cost of capital (ACC) is the annual levelized repayment over the project lifetime. It is considered that TPC comes from a loan at the beginning of the project. The variables used include the project lifetime, n, and the interest rate, i.

$$ACC = TPC \ x \ \frac{i(1+i)^n}{(1+i)^n - 1} \quad (13)$$

	Default(%)	Range (%)[12]
Direct cost		
Purchased equipment installation	47	15-40
Instrumentation & Controls (installed)	36	2-12
Piping	68	4-17
Electrical system	11	2-10
Buildings	18	2-18
Yard improvement	10	2-5
Services facilities	70	8-30
Indirect cost		
Engineering and supervision	33	4-20
Construction expenses	41	4-17
Legal expenses	4	1-3
Constructor's fee	22	2-6
Contingency	44	5-15
Working capital (%)	-	10-20

Table 10. Percentage of fixed-capital investment . *Source:* (Peters, Timmerhaus, & West. 2003)

[12] (Peters, Timmerhaus, & West, 2003)

4.1.3 Operational cost

4.1.3.1 Feedstock

The biomass feedstock used in this work is pellets and it is assumed to be supplied commercially by farmers. As there is no commercial information about this products in Argentina neither in Chile, reference price were taken from studies (Yang, Wang, Chong, & Bridgwater, 2018), (Yang Y. , et al., 2017), and (Trippe, Fröhling, Frank, Stahl, & Henrich, 2010) and (Trippe, Fröhling, Frank, Stahl, & Henrich, 2010). The price varies in a range between 40€/tn to 250€/tn of biomass pellets.

4.1.3.2 Fuel

As it mentioned previously, a blend of biodiesel and pyrolysis oil is used in a volumetric relation of 1:1. This ratio ensures the correct function of the CHP unit. The biodiesel is consider as an external raw material for the system, and hence it is just an output for the process and its elaboration will not be taken into account. The price of the biodiesel used in this work was calculated according to commercial prices. As the many variables determinate this price, a range price was used between 0,5€/l and 0,8€/l.

4.1.3.3 Utility cost

Utility cost includes the electricity and the water consumed by the system. This means, the electricity and cooling water used for drying process, intermediate pyrolysis process and CHP systems.

Electricity is an external input of the system. It is provided by the grid to secure the operation of the plant. The consumption of electricity includes not only the ones directly related with the plant, such as electrical operation equipment like a pumps, but also offices and general illumination. The lack of relevant literature information on this topic as regards intermediate pyrolysis processes leads to an estimated consumption of electricity.

Nevertheless, according to (Yang, Wang, Chong, & Bridgwater, 2018) and (Yang Y. , et al., 2017) the electric demands are 28 kWh per ton of feedstock and 36 kWh per ton of feedstock respectively. Adopting this range of values to the present work seems reasonable, as both case study involved integrated intermediate pyrolysis system with heat and power production.

The average price cost of electricity in Argentina for general industrial consumer (installed capacity: 0–8 MW) for the month of April was 0,04304 €/kWh (Ente Nacional Regulador de la Electricidad, 2019).

The average price cost of electricity in Chile was estimated on the basis of the report (Chile, Ministerio de Energia-Gobierno de, 2017) that forecast different scenario of electricity price. In this case using the standard lifetime of the plant was used to adjust the period of study and estimate the average cost of electricity over this period. The average price cost electricity in Chile was estimated in 0,042 €/kWh.

4.1.3.4 Labour cost

The lack of commercial existing plants makes labour force calculation difficult to compute. Nowadays plants are in a testing period and the real demand of labour force is difficult to estimate.

To estimate the workforce requirement the next table 11 was used as reference. As the number of employee depends on the size of the plant, to calculate the exact staff number, linear interpolation using as intervals those shown on table 11 were used.

Capacity (Kg/h)	**200**	**600**	**1000**	**5000**
N° Employee	10,5	14	14,5	18
Salary (€/year)	54.662	54.662	54.662	55.042

Table 11. Staffing and cost . *Source:* (Yang, Wang, Chong, & Bridgwater, 2018) (Yang Y. , et al., 2017)

The staff includes the whole human resource structure: managers, supervisors, administrators and operators. To estimate the annual cost of labour force an average cost per employee was used.

4.1.3.5 Plant maintenance and overheads

The annual maintenance and overheads cost were estimated as percentage of the TPC. Although this percentages vary, they are in a range between 2-5 % in the case of maintenance cost and 2-3 % for overheads (Peters, Timmerhaus, & West, 2003).

However, in order to be in line with previous works, 2,5% for maintenance and 2% for overhead were assumed as standard values.

4.1.4 Energy product sales

4.1.4.1 Electricity and heat sales

Different electricity scenarios with different selling prices were considered to evaluate the cost-effectiveness of the integrated system taking into account that energy products will be sold in different markets. Nevertheless, prices form the electric market of both countries for the month of April were used as reference.

The average cost of electricity for final general consumers in Chile, has a price of 0,11 €/kWh according to Enel (Enel - Tarifas Vigentes, 2019).

As for Argentina, the electricity is assumed to be sold to domestic consumers (residential houses) at an average rate of 0,0569 €/kWh according to the price publish by the ENRE (2019 C. T.-A., 2019) (National Electricity Regulatory Organism).

The lack of reference for the heating prices lead to assumed a price used by (Yang, Wang, Chong, & Bridgwater, 2018) of 0,0403 €/kWh. It must be noticed that, in Argentina and in Chile, as well, there is not a heating network for selling this type of energy yet. However, in this work, the assumption of an existing network is used in order to be able to sell heat as a final product.

4.1.4.2 Char

To determine the selling price of char the report made by the Ministry of Energy of Chile is used (Chile, Ministerio de Energia-Gobierno de, 2017). Biochar is a secondary product sale and is not the aim of this work to analyse it influence. So, in order to be able to use the same value for both scenarios, Chile and Argentina, a reference price will be taken from table 59 of this report that indicates the price of carbon in USA. The report suggested a maximum price of 54 US$/Tn and a minimum price of 53 US$/Tn for the year 2018. The assumed price adopted is 50 €/Tn taking into account the exchange rate. Furthermore, it is necessary to consider that the assumed price corresponds to a carbon with a higher heating capacity, and therefore with a higher commercial value.

4.1.4.3 Renewable energy incentives

Renewable incentives depends on energy politics and measures assumed by each country. Every country has different resources to produce energy which leds to highly diverse energetic matrixes. As it is well known, in Latin American countries, the participation of renewable energies is still low. According to (ASOCIACIÓN DE GENERADORAS DE CHILE, 2018), the installed capacity of renewable generators in Chile is 47% and in Argentina in the year 2016 this percentage just reached 1,7% (Subsecretaria de Planeamiento Energetico Estrategico, 2016). The lack of market where Renewable Obligations or Renewable Heat Incentives can be traded because the only tool to promote renewable energies that governments have is through subsidies to renewable electricity production, this means producers receive X amount of US$ per MWh of energy produced.

In the case of Argentina, the subsidy rate assumed for this case study was the incentive offer in “Programa RenovAr Ronda 2” (Ministerio de Energia, 2017) an International Bid launched by the Ministry of Energy to promote renewable energies. In this bid, where 100 MW installed capacity of biomass energy was tender, a special incentive was given for this type of technology. This incentive was for generators whose installed capacities were less than 15 MW. The incentive R assumed in this work was taken from this bid and its work according to the next equation x:

$$R = 40 - \left(\frac{15 - p}{14{,}5}\right) [US\$/MWh] \tag{14}$$

$$p = installed\ power\ capact.icy\ [MW]$$

$$R = rate\ of\ subsidy$$

As for Chile, the subsidy assumed belongs to the amount received by carbon plants and it is a fixed amount (Valdivia, 2010). Although it is an old value, as it is not in the scope of this work to analyse renewable incentives, this value is assumed:

$$R = 10\ [€/MWh] \tag{15}$$

4.1.5 Levelized cost of energy

The concept of "levelized cost of energy" (LCOE) is a widely accepted measure in the energy industry, which facilitates useful comparisons to be made across different energy technologies, geographical sites and different research studies (Ansuategui, Delgado, & Galarraga, 2014).

The LCOE stands for the minimum price at which electricity can be sold so that all energy production cost are covered. As the integrated systems analysed may sell heat and energy carriers the calculation of the LCOE assumes that this products can be purchased by the market.

As it was explained in the previous section, government incentive subsidies are also considered as an income in the calculation of the LCOE.

The LCOE is estimated by using the next equation 16:

$$LCOE = \frac{ACC + OP - S - (Q_{elec}\ x\ R_{elec})}{Q_{elec}} [€/kWh] \tag{16}$$

$$ACC = anual\ capital\ cost\ [€];\ \ OP = annual\ operating\ cost\ [€];$$

$$S = annual\ sales\ (heat\&energy\ products)[€];\ \ Q = annual\ electricity\ prodcution\ [kWh];$$

$$R = rate\ of\ incentive\ subsidy\ [€/kWh]$$

4.1.6 Internal rate of return

Another tool used to size and assess the profitability of different projects investment is the internal rate of return (IRR). In this work, it will represent another variable of comparison between the different integrated systems.

The IRR is defined as a discounted cash flow rate of return that makes the net present value (NPV) of cash flows equal to zero.

For calculating the NPV, each individual annual net cash flow is actualized to present values (PVs) and then sum up. The PV represents the cash flow in future that has been discounted to reproduce its present value as if it existed today.

The following equation 17 is used to calculate the NVP:

$$NVP = -C_0 + \sum_{t=1}^{T} \frac{C_i}{(1+r)^t} + C_{sv}[€] \quad (17)$$

$C_0 = initial\ investment\ [€];\ \ C_i = cash\ flow\ [€]; r = discount\ rate; t = year$

$T = project\ lifetime;\ C_{sv} = salvage\ value\ of\ the\ equipment$

For calculating the NPV, each individual annual net cash flow is updated to present values (PVs) and then sum up. The PV represents the cash flow in future that has been discounted to reproduce its present value as if it existed today.

5 Results and discussions

5.1 Results

5.1.1 Overall process efficiencies

In this section the overall efficiencies of both alternative systems will be compared. Table 12 and table 13 present the different efficiencies taking into account different types of biomass and different pyrolysis temperature.

IP temperature		500° C	600° C	690° C
Agricultural by-products	Electric efficiency(%)	5	3	6
	Heat efficiency(%)	72	22	51
Overall efficiency %		52	25	57
Wood	Electric efficiency(%)	7	3	6
	Heat efficiency(%)	67	23	53
Overall efficiency %		74	26	59

Table 12. Pyro-CHP system efficiencies . *Source: Own made*

IP temperature		500° C	600° C	690° C
Agricultural by-products	Electric efficiency(%)	13	19	9
	Heat efficiency(%)	0	0	0
Overall efficiency %		13	19	9
Wood	Electric efficiency(%)	9	18	9
	Heat efficiency(%)	0	0	0
Overall efficiency %		9	18	9

Table 13. Pyro-Micro biogas turbine efficiencies*. Source: Own made*

As it is shown efficiencies vary depending on the type of biomass and the temperature of the pyrolysis reaction. It must be noticed that, although the elementary composition of each type biomass is similar they are not equal. As described in section 2.4.1.1., the intermediate pyrolysis reactor transform the biomass into bio-oil, biogas and char obtaining different mass which affects the efficiencies.

Alternative 1, the integrated system with two CHP unit has 3 mainly parts where loses occur:

- During the drying: generally the dryer has an efficiency of 70% when transferring the heat to the biomass. Most of this heat is taken away by the water vapour.

- During the pyrolysis reaction: the reactor has a general efficiency of 70%. The loses include heated absorbed by the remaining moist and by heat transfer from the reactor to the biomass. The lost heat ends mostly in the ambient.
- During the combustion of the char: apart from the general efficiency of the char combustor, which generally 65% there are also loses when transferring this heat to the IP reactor, as the temperature must be adjusted to the required one.

Alternative 2, the integrated system with a microturbine unit has 3 mainly parts where loses occur. In the first two steps loses are equivalent to the ones mentioned above. The difference is on the third step

- During the bio-gas combustion in the gas turbine: the heat discharged in the flue gas, which is then used to heat the IP reactor, has to be adjusted to the correct temperature and there is also a loss of energy during the transfer to the reactor.

If this systems were supposed to be used in an industrial integrated process, these losses should be reduced to the minimum in the way that the maximum overall system efficiency is obtained.

It was mentioned in chapter 3 that the efficiencies values assumed in the spread-sheet model might have uncertainty and are based on standard equipment. And consequently may affect the global efficiency of the products. That is why a simulation in Aspen Plus simulator was carried out to obtain others efficiencies and then replaced in the spread-sheet model. The next table 14 displays the results of modifying the dryer and the combustor efficiency by $\pm$ 20% and how it impact on the global efficiency of the system. This effects were analysed on Soya Straw biomass.

		∆Global Pyro-CHP Efficiency	∆Global Pyro-CHP Efficiency
Dryer Efficiency	∆+20%	+1%	+1%
	∆-20%	-2%	-2%
Combustor Efficiency	∆+20%	+2%	0%
	∆-20%	-3%	0%

Table 14. Dryer and combustor efficiency impact*. Source: Own made*

Looking at the table above, the first conclusion it can be made is that as both process implies several thermal steps and processes, when modifying just one variable and leave the others constant, the impact on the global efficiency is small. When comparing the combustor with the dryer an improvement in the first one will supposed a higher impact in the global efficiency.

5.1.2 Levelized cost of electricity: LCOE

To analyse the levelized cost of electricity the standard values assumed above, in chapter 4, were used. In order to compare both scenarios, Argentina and Chile, residual soya straw was selected as input biomass, as it is produced in both countries and at temperature of 500° C for the pyrolysis reaction for both alternative systems. By the way, the installed capacity selected as standard was 25.000 Tn of wet biomass per year.

The next figures show the calculated LCOE and its breakdown into project costs, that includes capital and operative costs, and earnings from subsidies and products sales. In the graphs the positive bars represent the direct cost associated to that cost while the negatives bars represent the incomes. When summing up all the values, each scenario provides a specific LCOE value for each case of study.

5.1.2.1 Evaluation of scenarios and alternatives

Alternative 1: Pyro-CHP

Figueres 22 and 23 display the result obtained from the integrated system with a bio-oil CHP unit and Biogas CHP unit to produce heat and power.

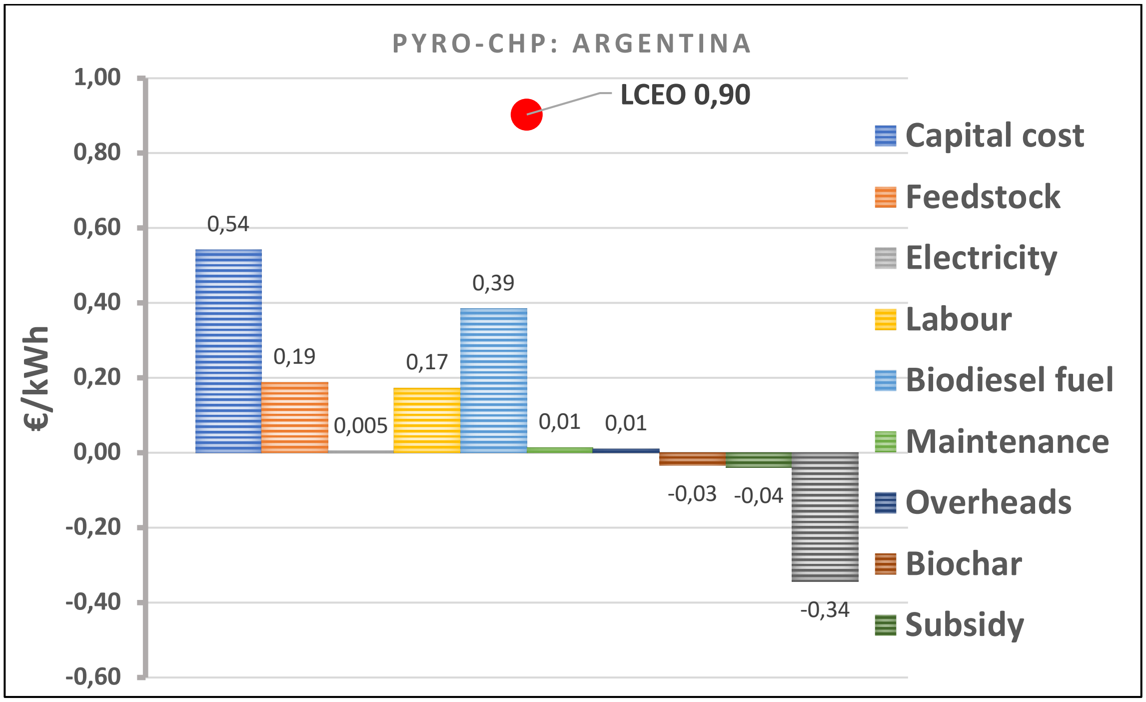

Figure 22. Levelized Cost of Electricity and its breakdown for Argentina*. Source: Own made*

As it is noticed in both figures, 22 and 23, the LCOE structure for both countries is almost equal. The main difference can be found in subsidy incomes, as different incentives were assumed for each country. As regard electricity costs, Capital accounts for approximately 40% of the electricity expense being the most significant contributing factor. Following this, it is the biodiesel cost, which is the highest operative cost with an average participation of 30% in the total cost. In less percentage but also important, labour and feedstock costs also contribute with around 25% when summed up together.

In the revenue stream, it is clear that the sale of heat represent the main income of the project, representing around of 80% of the earnings. The rest come from the sale of biochar and subsidy.

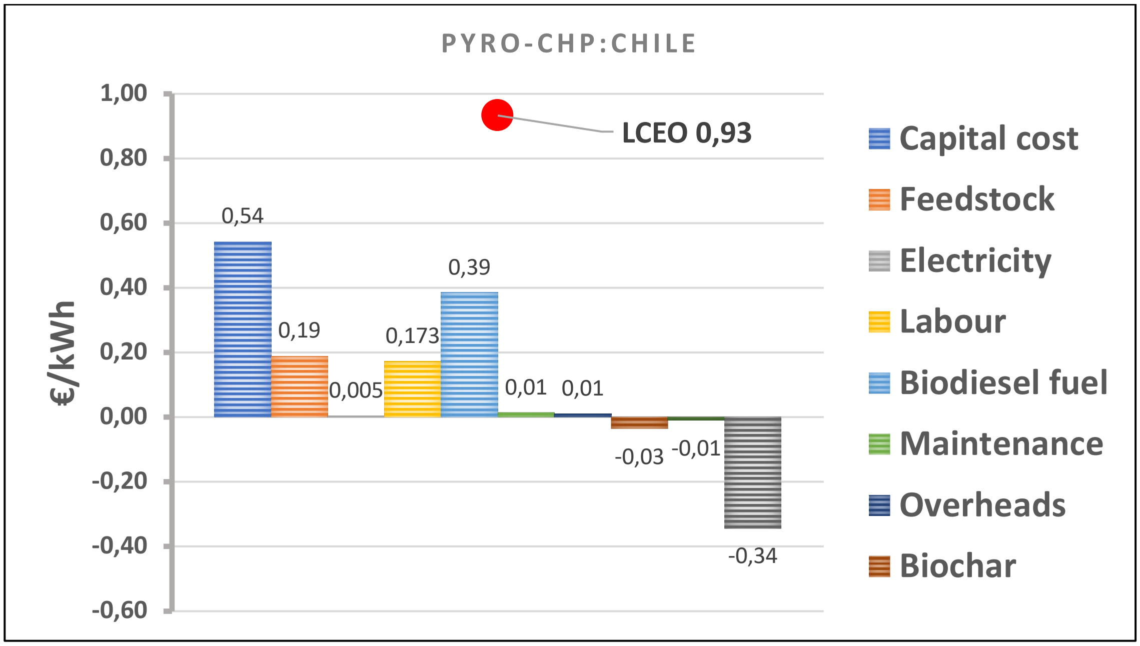

Figure 23. Levelized Cost of Electricity and its breakdown for Chile*. Source: Own made*

Alternative 2: Pyro-Micro biogas turbine

Figueres 24 and 25 displays the result obtained for the integrated system with a micro biogas turbine.

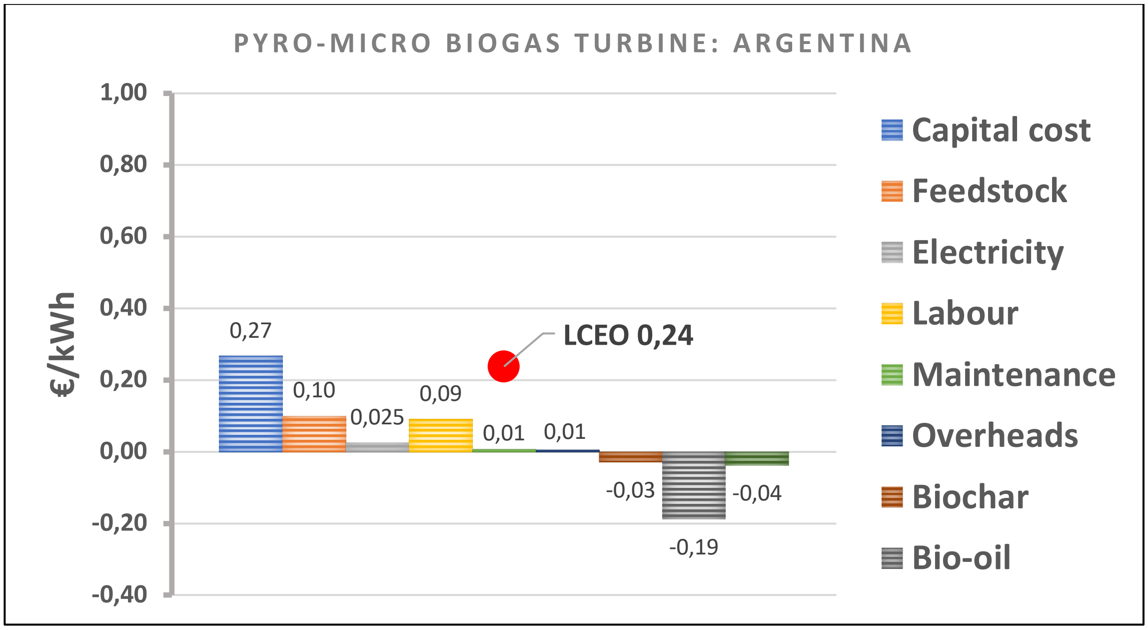

Figure 24. Levelized Cost of Electricity and its breakdown for Argentina*. Source: Own made*

As it is noticed in both figures, 24 and 25, the LCOE structure for both countries is almost equal. The main difference can be found in subsidy incomes, as different incentives were assumed for each country. As regards electricity costs, Capital accounts for approximately 50% of the electricity expense being the most significant contributing factor. Following this, it is labour and feedstock operative costs that contribute with around 39% when summed up together.

In the revenue stream, it is clear that the sale of bio-oil represent the main income of the project, representing around of 80% of the earnings. The rest comes from the sale of biochar and subsidy.

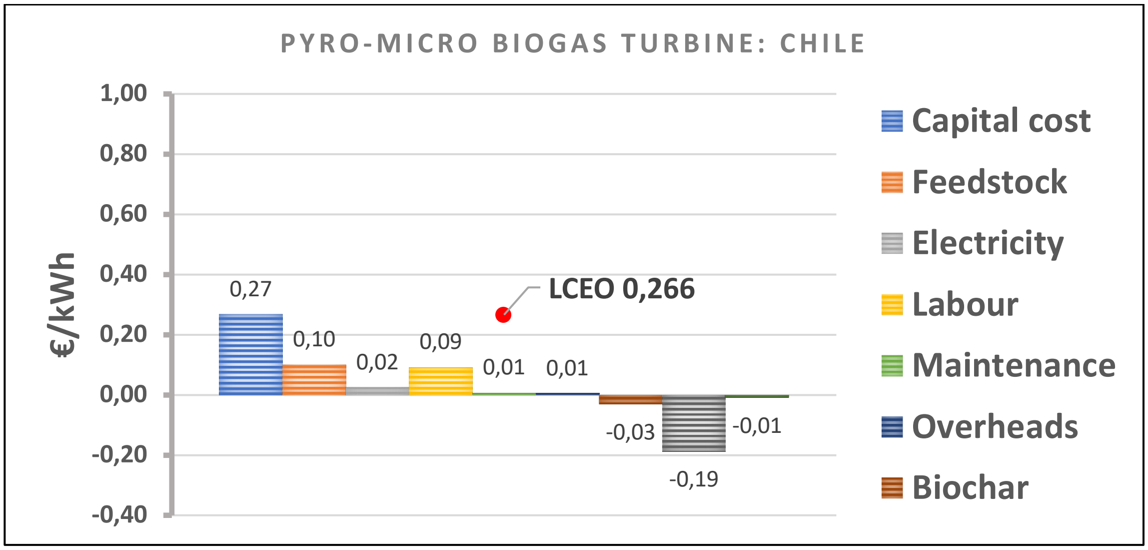

Figure 25. Levelized Cost of Electricity and its breakdown for Chile*. Source: Own made*

<u>Comparative LCOE</u>

When comparing LCOE results, the first thing to be noticed is that this value is significantly lower in alternative 2 than in 1. The main reasons are:

- Total capital cost investment in Pyro-CHP system is 10% higher than alternative 2. This is main difference is due to the required investment in the two CHP units.
- Operative levelized cost such as labour and feedstock are lower in Pyro-Micro Biogas turbine because the annual production of electricity is higher in (50% higher).
- The overall efficiency to produce electricity is higher in Pyro-Micro Biogas system, as it uses a micro biogas turbine with an electrical efficiency in a range of 35-45% against CHP units in Pyro-CHP system that has an electrical efficiency around 10%

LCOE

The LCOE values obtained for Pyro-CHP system were 0,9 €/kWh for Argentina's scenario and 0,93 €/kWh for Chile's scenario. The obtained results do not fill well in the values obtained from others´ works. According to (Ministerio de Energia - Gobierno de Chile, 2017) the average costs for this technology, biomass cogeneration, is 0,178 €/kWh in Chile and 0,158 €/kWh in Argentina, according to (Vignolo & Vizzolini, 2017). Although LCOE seems not to be competitive, later, it will be shown that when scaling up the project the LCOE values obtained are more near to those described above.

The LCOE values obtained for Pyro-Micro Biogas turbine were 0,24 €/kWh for Argentina´s scenario and 0,26 €/kWh for Chile´s scenario. The obtained results does fill well in the values obtained from others works. According to (Ministerio de Energia - Gobierno de Chile, 2017) the average cost for this technology, agricultural biomass, is 0,137 €/kWh in Chile and 0,130 €/kWh in Argentina, according to (Vignolo & Vizzolini, 2017). The LCOE values calculated look reasonable and competitive. Although being over the level suggested by other works, when scaling up the plants, the LCOE is in the range of the one in the actual market.

5.1.2.2 LCOE: scale up effect

In this section, the influence of scaling up the plants will be presented. Figures 26 and 27 illustrates the scale effect. As it is observed, when increasing the plant size the LCOE tends to reduce, as cost are absorbed by a higher production level. Comparing LCOE to three different levels of production scaling up by 40% led to a reduction of around 55% in average of the LCOE values for Pyro-Micro Biogas turbine and an average around 75% for Pyro-CHP systems.

Furthermore, as it was mentioned above, when having an installed capacity of 35.000 Tn/year the LCOE values for Pyro-Micro Biogas turbine are almost equal to the market prices, allowing to affirm that for those levels of productions Pyro-Micro Biogas turbine has the potential to compete in the market and be profitable. When analysing alternative 1, although it does not reach competitive levels of LCEO, the fact that the scaling up factor is really high (75%) gives the idea that with the right plant size it can become a competitive technology in the market.

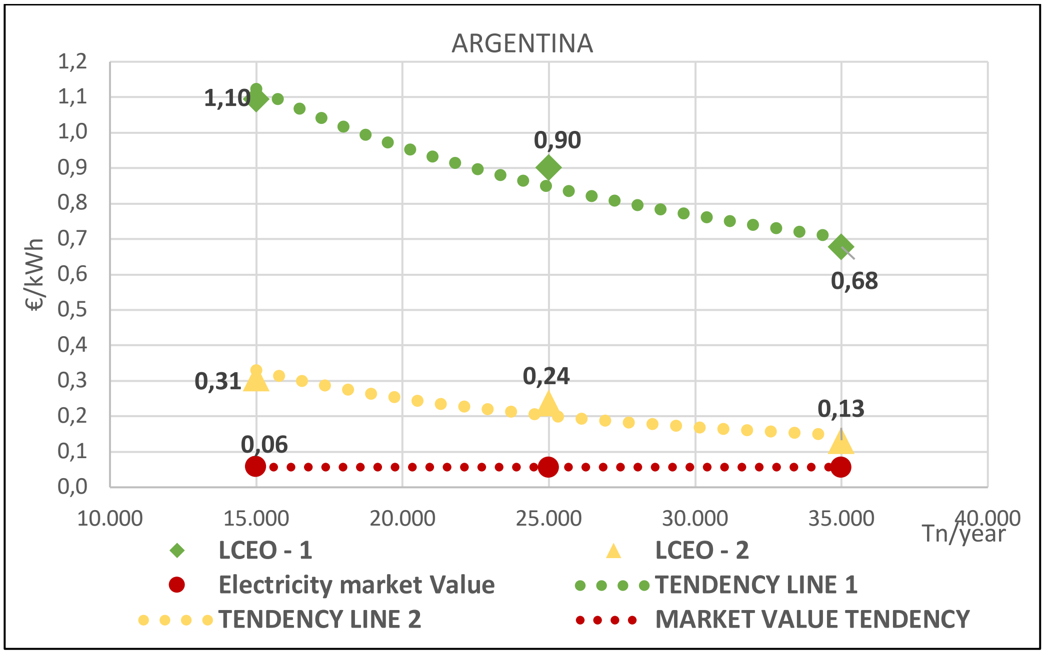

Figure 26. Comparison of estimated LCOE and Argentina market values. *Source: Own made*

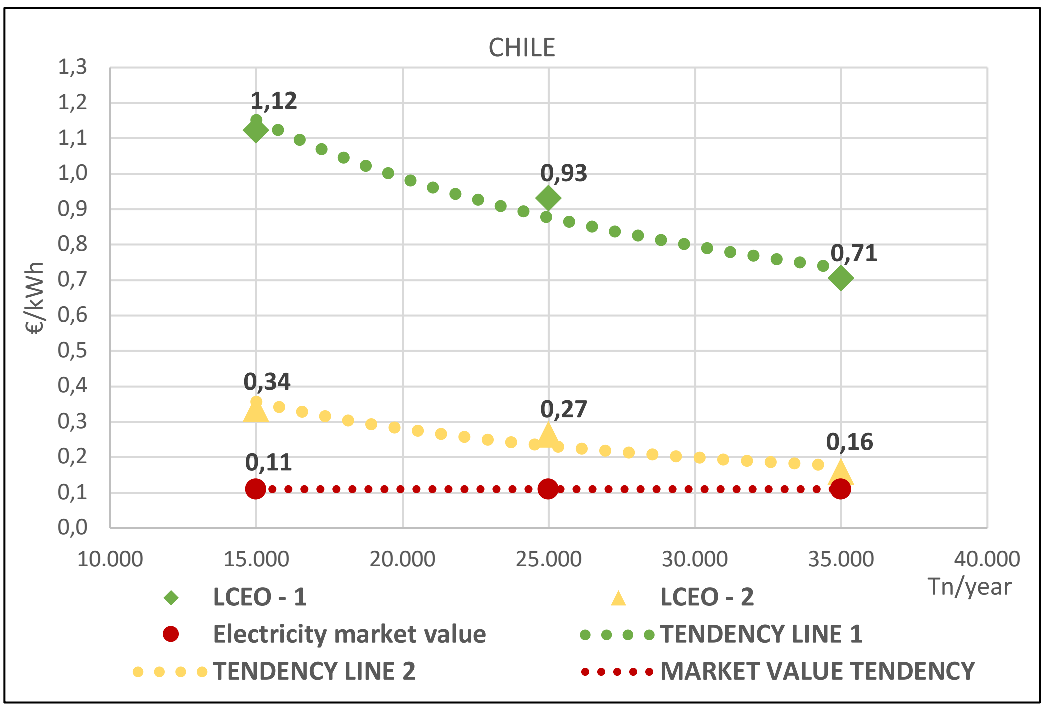

Figure 27. Comparison of estimated LCOE and Chile market values. *Source: Own made*

Global LCOE from utility-scale renewable power generation technologies

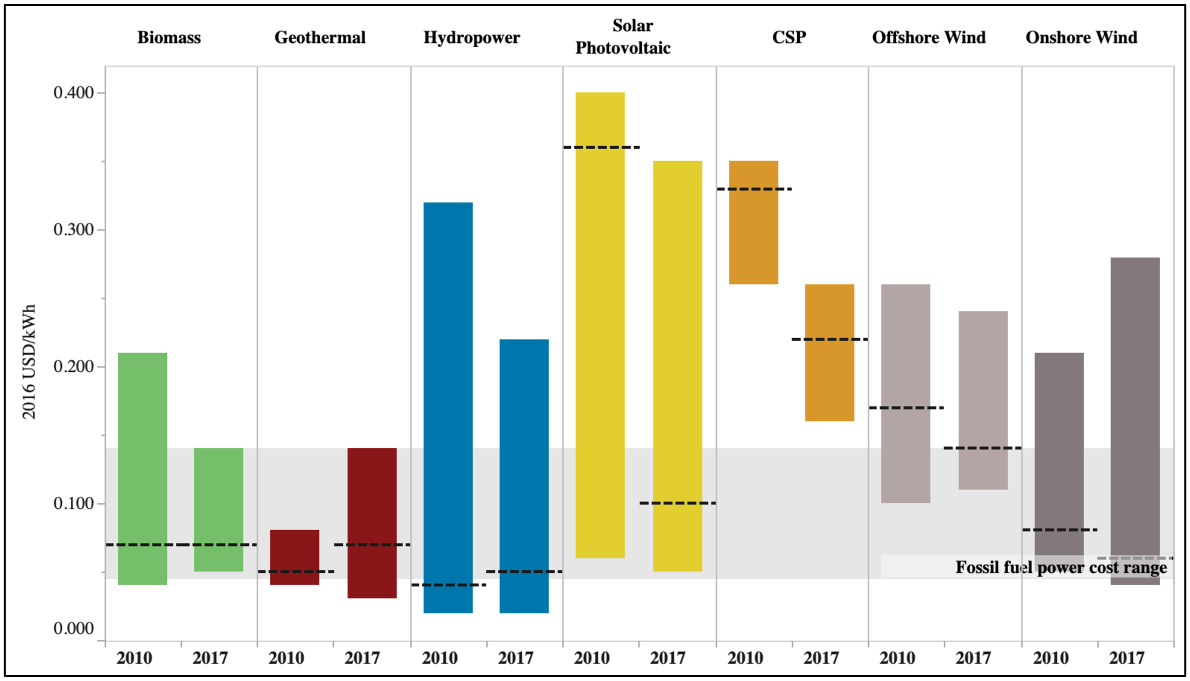

Figure 28.*LCOE values for renewable energies technologies. Source: IRENA Renewable Energy Cost Database*

According to IRENA database (IRENA,The International Renewable Energy Agency, 2017), the LCOE for biomass has an average value of 0,07 €/kWh. This value is considerably down the best scenario assumed, which best result for LCOE was 0,13 €/kWh, almost the double. Nevertheless, when comparing with other renewable technologies such as solar photovoltaic or wind power the LCOE for biomass is lower.

5.1.3 Sensitivity analysis

The aim of this section is to demonstrate the influence of the most representative variable of the project and how by increasing or decreasing their impact on the LCOE. This analysis will permit to find the critical variables of the project and to put a focus on them in order to reduce the value of LCOE. As there are many variables in the project, the criteria for selection was to consider those that vary, at least $\pm$ 1% of LCOE when modifying the variable value in $\pm$ 20%. The sensitivity analysis will be based on 25.000 Tn/year size plant, based on soya straw and an intermediate pyrolysis temperature process of 500°C.

5.1.3.1 Evaluation of scenarios and alternatives

Alternative 1: Pyro- CHP

Figueres 29 and 30 displays the result obtained for the integrated system with a bio-oil CHP unit and Biogas CHP unit to produce heat and power.

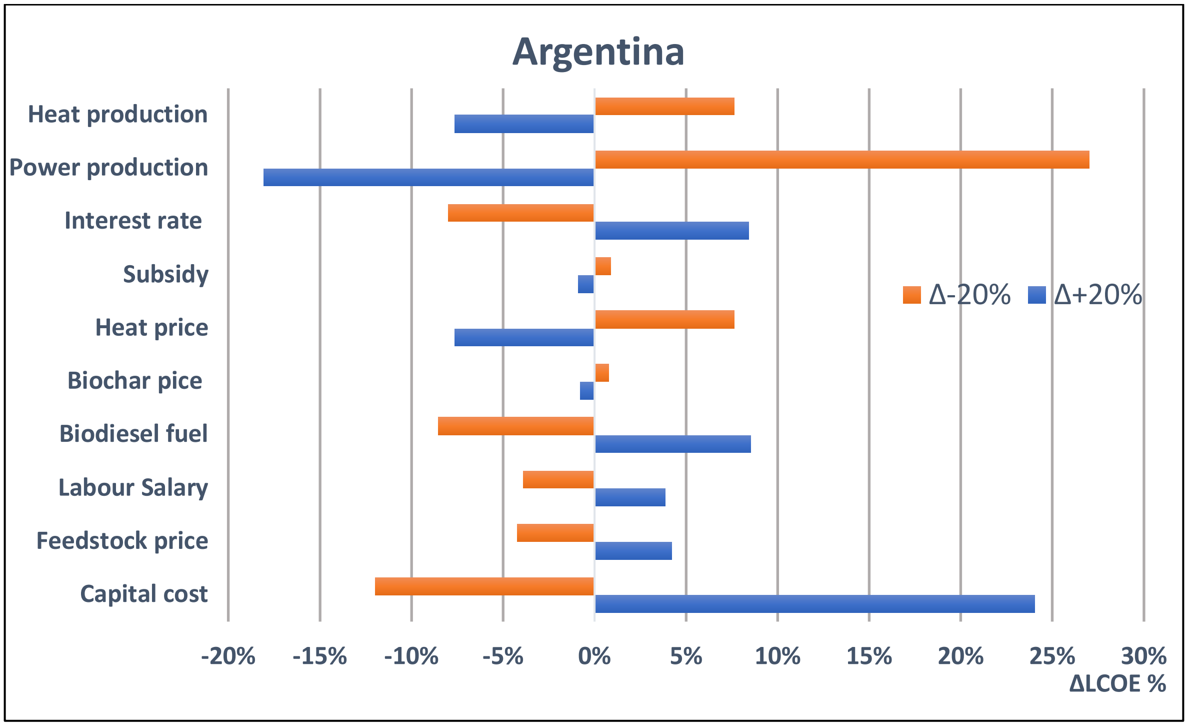

Figure 29. Sensitivity analysis for estimated LCOE (based on a 25.000 Tn/year). *Source: Own made*

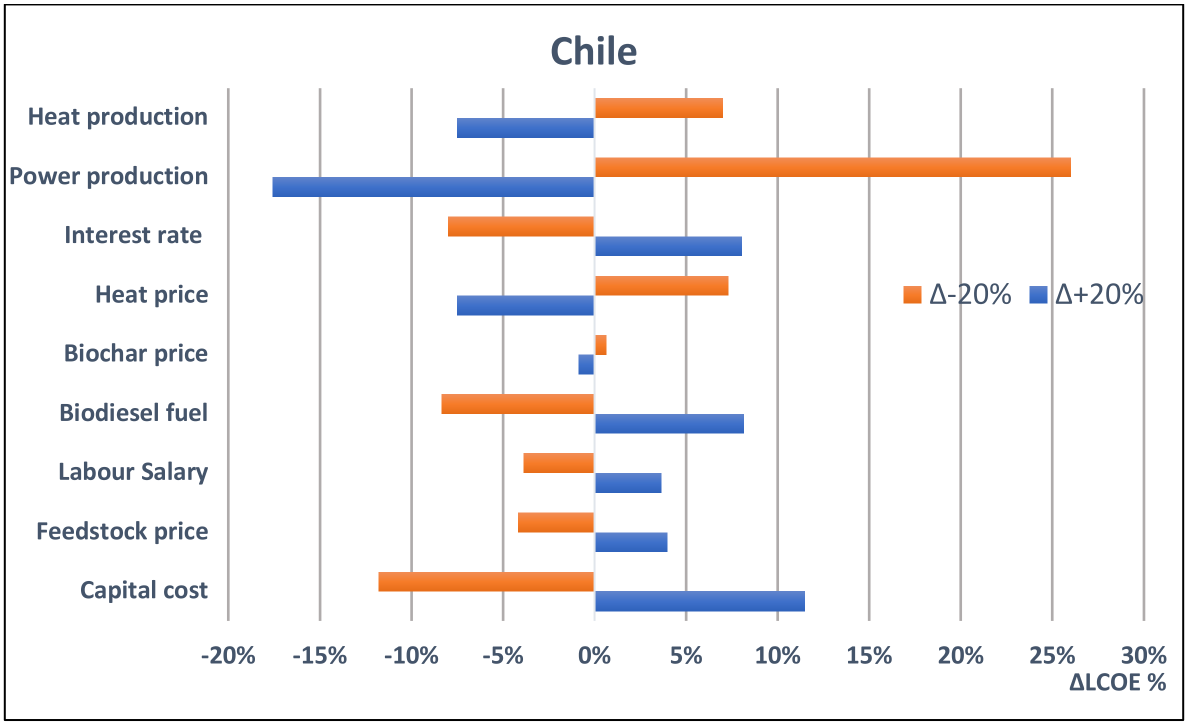

Figure 30. Sensitivity analysis for estimated LCOE (based on a 25.000 Tn/year)*. Source: Own made*

As it is noticed in both figures, 29 and 30, the ΔLCOE structure for both countries is similar. The difference is that for scenario performed in Chile, the variable subsidy does not appear as a relevant variable to the project. The reason for this, is that the incentive to this kind of project assumed in this work was much less than the scenario developed for Argentina. The most critical variables for this integrated system seems to be in the first place, power generation and then capital cost. A variation of 20% in electricity productivity can reduce or increase the LCOE 18% or 26%, respectively. In the second place of importance, appears capital costs, which due to the big investment required for this type of plant, they can decrease or raise LCOE by 12% in both ways.

Last but not least, it is important to mention variables which impact is not as big as the previous ones mentioned but can contribute to reduce the LCOE. These variables are in order of importance: biodiesel fuel price, interest rate, heat production, heat price, feedstock price, labour and biochar price.

The reader must notice that the impact of the dryer and combustor efficiency variation was carried out although their impact on the LCOE was minimum. this leads to the conclusion that from the economic point of view the impact of this variables does not affect the viability of the project.

<u>Alternative 2: Pyro-Micro biogas turbine</u>

Figueres 31 and 32 displays the result obtained for the integrated system with a bio-oil CHP unit and Biogas CHP unit to produce heat and power.

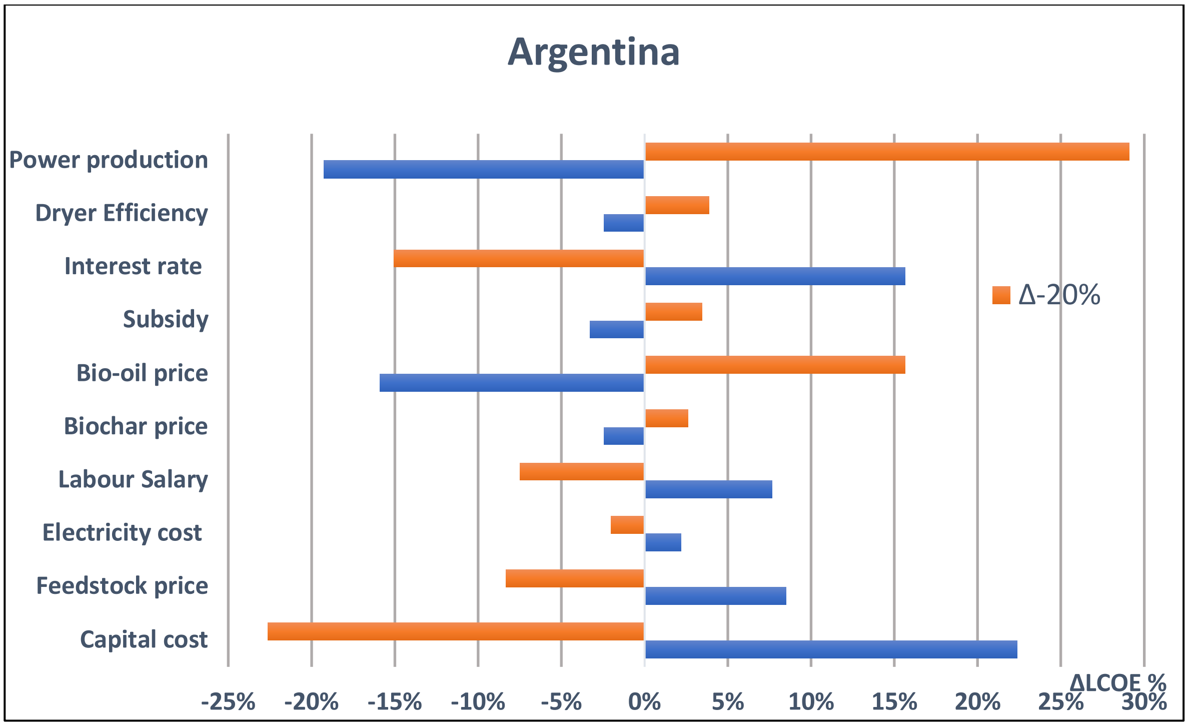

Figure 31. Sensitivity analysis for estimated LCOE (based on a 25.000 Tn/year). *Source: Own made*

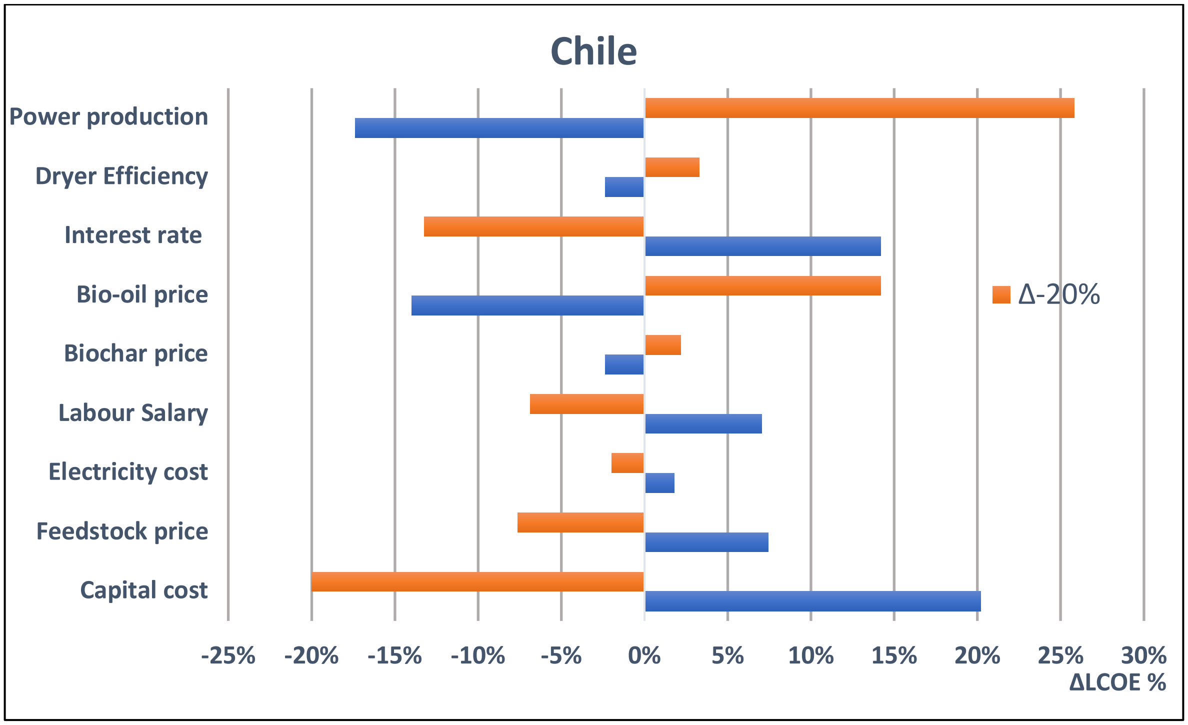

Figure 32. Sensitivity analysis for estimated LCOE (based on a 25.000 Tn/year)*. Source: Own made*

As it is noticed in both figures, 31 and 32, the ΔLCOE structure for both countries is similar. Once again the difference is that of the scenario performed in Chile, the variable subsidy does not appear as relevant variable to the project. The reason for this, as it was explained, is that Argentinian incentives are, in average, 4 times Chileans. The most critical variables for this integrated system seem to be, in the first place, power generation and then capital costs. A variation of 20% in electricity productivity can reduce or increase, in average, the LCOE 18% or 26%,respectively. In the second place of importance, capital cost appears, due to the big percentage of the investment in the total cost of plant can decrease or raise LCOE by approximately 20% in both ways.

Following in importance is the bio-oil price variable. This variable represent a high income, as the whole production of this product is assumed to be sold. The variation of this variable can cause a variation of almost 15% in the LCOE. Similar consequences are produced by a deviation of the interest rate.

Finally, variables which impacts result in less than a 10% variation in the LCOE. This variables are: biochar price, labour salary, electricity cost and feedstock price. These variables might not represent significant changes but if they are added up together an important reduction in LCOE can be made.

In this case the dryer efficiency variation is more significant reaching a value around $\pm$ 3% when improving o decreasing its efficiency in 20%. Although from the economic point of view it will not affect the viability of the project, it must be consider when trying to reduce the cost to the minimum.

5.1.4 Internal rate of return

Figure 33 clarify that this kind of projects are still not attractive from the investment point of view. The IRR obtained was based on an Pyro-Micro Biogas turbine plant standard with the maximum size available (30.000 tn/year) and it was estimated including the cost of generation, product sales, and earning of the integrated system during it life project (20 years).

As regards the other scenarios studied, the results thrown up were negative or with lower IRR. This means that annual earnings during the project life time are not enough to cover the capital cost.

In the case of using maximum capacity of an integrated system plant with a micro biogas turbine, IRR turns positive and makes the projects profitable. Nonetheless, the values displays in figure 33 are too low taking into account that normally a minimum of 10% is required. Furthermore, this work does not take into account the risk of investing in this new renewable markets which are in a phase of development. According to (Yang, Wang, Chong, & Bridgwater, 2018), these risky operations are attractive if the IRR is around 25%.

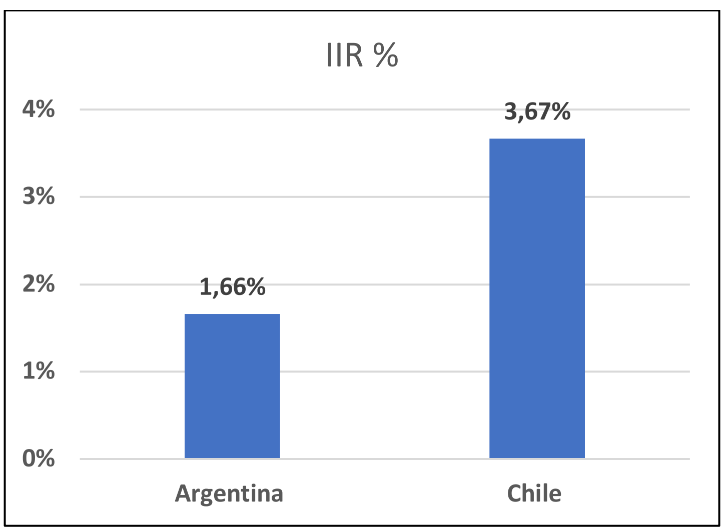

Figure 33. Internal rate of return estimation (based on a 25.000 Tn/year). *Source: Own made*

6 Discussion and conclusion

6.1 Discussion

To perform this evaluation on pyrolysis integrated system the method used was based on literature research. Despite obtaining comparable results with other similar works, some limitations can be mentioned in order to improve them with further works.

To begin with, the intermediate pyrolysis is still in a stage of development and the information taken from the literature are experimental results. This processes were based on 3 experiments held out using biomass which origin is not from Argentina or Chile. Nevertheless this yields were assumed and used for estimating the plant production. This led to many possible configurations taking into account the temperature, type of biomass and residence time and consequently many possible outcomes

Thermodynamics properties and behaviour also required to used information which was not precise. Characteristics like specific heat capacity and it temperatures were estimated using linear approximations which introduce uncertainty.

Next, in the economic evaluation to calculate the capital demanded for the plant model allocates incremental factors which are assumed from another similar work but in reality can vary significantly. This factors multiply by 5 the direct cost, so they make a great difference. Although according to (Peters, Timmerhaus, & West, 2003) when developing this kind of study the uncertainty of cost is $\pm$ 20%, it would be interesting to make a further research on this factor to obtain more accurate results.

The approach taken, stablish conditions downstream and upstream the stablish boundaries of the system that in reality may occur or not. For example the constant provision of biomass or that the total production can be located in the market at a constant price. Another clear example of this are the subsidies values assumed, which for this type of process to be profitable in the selected context are essential. This assumptions could be studied with further detail in the future so that the complete chain value can be completed.

It was shown all over this work, this whole model is based on many variables: thermodynamics properties, economic factors, prices, subsidies, efficiencies among others which are not constant in time and may change. That is why, this kind of evaluation will always have uncertainty, but in the future it would be interesting to reduce this uncertainty to the minimum.

Finally, the future of TCR technology looks promising. Commercial projects like "the carbonauten" (Carbonauten, 2019), which converts any type of organic waste into "biocarbons" that can then be burned later to obtain power or heat. Another interesting initiative to be mentioned is “2SYNFUEL” (Horizon 2020 EU's, 2019), an international European project involving several countries which use sewage sludge as an input for a TCR process that produce bio-oil, H_2 rich synthesis gas (SYNGAS) and biochar (uses as a soil amendment).

6.2 Results

The results of this master's thesis model and simulation have been satisfactory, firstly because it has been possible to develop a model that simulates different processes where economic and technical parameters can be evaluated. And secondly, the whole model as an outcomes provides the LCOE which is the main parameter used nowadays to compare energy generation technologies. Furthermore, it also permit to compare different scenarios and alternative integrated systems.

According to the results showed, a standard Pyro-CHP plant processing 7000 Tn of soya straw has an overall average efficiency of around 66%. The most important losses of this system are due to the heat required for reducing the moist and maintaining the temperature of the intermediate pyrolysis reactor. Also loses caused by the heat transfer from combustor. The overall efficiency is similar to other works like (Yang, Wang, Chong, & Bridgwater, 2018) that although it uses municipal waste, the integrated system is almost the same. Depending the context, the levelized cost of energy is approximately 0,9 €/kWh. This cost is over the market price and so turns the project not profitable. However this price can be optimised to the minimum by: scaling up; reducing key factors such as capital cost; and increasing the power production.

Regarding to the results showed by the standard Pyro-Micro biogas turbine plant model processing 7000 Tn of soya straw has a global average efficiency of around 63%. The most important losses of this system are due to the heat required for reducing the moist and maintaining the temperature of the intermediate pyrolysis reactor. Also loses caused by the heat transfer from flue gas to the dryer. Depending the context, the levelized cost of energy is approximately 0,25 €/kWh. Although this cost is over the market price and so turns the project not profitable when scaling up this integrated system reaches values that can make the project profitable by optimising critical factors. For example, by reducing capital cost; obtaining better biodiesel price or getting a better discount rate.

According to OpenEI (OpenEI, 2019) the LCOE estimated are over the average for this type of technology. According to this database the LCOE for this technology is around 0,09

€/kWh, half of the best case scenario LCOE calculated. However, when comparing with other technologies such as solar photovoltaic the LCOE is lower.

6.3 Conclusions

This research has presented the outcomes of a techno-economic study on two conceptual models: a Pyro-CHP plant and a Pyro-Micro-turbine plant. Both models were based on experimental intermediate pyrolysis yields and evaluated in an Argentinian and Chilean context.

The first conclusion that can be pointed out is that, with the actual context, this kind of project are not feasible from the economic point of view. The LCOE and the IRR estimated makes this plants not attractive for investors yet. Nevertheless, scaling up the plants, and making a reduction in vital factors such as capital cost or increasing power and heat production the LCOE obtained can reach values that may compete in the energy market.

From the technical point of view, the projects look very attractive. The overall efficiency is an a range of 50-60%, which is higher than conventional energy generators such as diesel or gas engines which have an overall efficiency around 40% (Dr. Fromme International - Consulting, 2016). Furthermore, the plants are based on agriculture or forestry wage, which is aligned with circular economy concept, taking advantage of unused resources. Another advantage to be mentioned, is that, taking into account the extension of the selected areas (Buenos Aires province and Araucania region) and the availability of waste biomass, this plants can be installed anywhere in this areas promoting the decentralization of energy generation and reducing the loses and cost in energy transport.

As for the electricity market, the main differences found between the Chilean and Argentine markets are the subsidized amounts granted by each country and in the selling price of electricity. While the Argentine government offers higher subsidies, the Chilean market offers higher prices. So in the end, conditions end up being very similar. A disadvantage that must be noticed is that, due to the instability affecting Latin America in general, the risk of this kind projects results high and difficult to quantify.

As for the future, intermediate pyrolysis processes appear as a possible solution to respond to the growing demand for energy in a sustainable manner. The greatest strength of this type of process when compared to other technologies is its flexibility, since it has the option of placing its products (power and heat or energy carriers) directly in the market or integrate it with other industrial processes, such as the cellulose industry to mention an example, which demand heat and energy.

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