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"Energy valorization of wood residues through a small scale open top gasifier"

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Contents

Abstract

In this work, the possibility of valorization of biomass residues have been investigated by means of experimental analysis on a small scale open top gasifier and the application of a thermodynamic model. Moreover the effect of the torrefaction pretreatment will be investigated through the gasification of torrefied pellet (processed a two different temperatures).

In the first part, the analysis of the data elaborated starting from national and local database (ISTAT Istituto Nazionale di Statistica and the Chamber of Commerce of Bolzano Province) with the aim of possible alternative feedstocks for a gasification process are presented.

In the second part, the results of the laboratory (Laboratory of Free University of Bozen) analysis performed on the chosen materials are shown.

In the third part, the data obtained from the gasification in a small scale gasifier have been elaborated and presented. The effect of different percentages of bark in wood chips have been investigated with the aim of evaluating the possibility of its valorization in a gasification plant. The results of the gasification tests have been also employed for the calibration of a model used for the gasification simulation of a compost out of specification (over sieve material) produced from a combined process of anaerobic digestion and composting.

Finally, an economic analysis on small-medium scale gasification plants applications have been performed in order to understand if a practical use of the analyzed feedstocks is possible (considering also the case of incentive absence). The evaluation of the possibility of residual valorization is of primary importance not only to achieve higher standards in terms of "zero waste" processes, but also for a future economic development of the technology, characterized by high potential of development, but, at the state of the art, by high costs of investments and management.

In dieser Arbeit kann die Entwicklung von Biomasse genutzt werden Mit anderen Worten, die Wirkung des Turms wird durch die Vergasung von torrefizierten Pellets (die bei zwei verschiedenen Temperaturen verarbeitet werden) erzielt.

ISTAT Nationales Statistikinstitut und Handelskammer der Provinz Bozen (ISTAT) mit Analyse der Datenverarbeitung.

Im zweiten Teil die Ergebnisse der Laboranalyse (Labor der Freien Universität Bozen)

Im dritten Teil wurden die Daten aus der Vergasung in einem kleinen Vergaser aufbereitet und präsentiert. Die Auswirkung unterschiedlicher Rindenwerte in Hackschnitzeln wurde untersucht. Die Ergebnisse des Vergasungstests sind die Hauptmerkmale des Vergasungstests.

Schließlich wurde eine wirtschaftliche Analyse für Vergasungsanlagen im kleinen und mittleren Maßstab entwickelt, um zu verstehen, ob eine praktische

Verwendung der analysierten Ausgangsmaterialien möglich ist (auch unter Berücksichtigung des Falls von Abwesenheit von Anreizen).

Die Bewertung der Möglichkeit der Restverwertung der "Zero Waste" -Prozesse, aber auch für die zukünftige wirtschaftliche Entwicklung der Technologie. Stand der Technik durch hohe Investitions- und Verwaltungskosten.

Nel presente lavoro, la possibilità di valorizzazione dei residui di biomassa è stata studiata mediante analisi sperimentali su un gassificatore open top su piccola scala e l'applicazione di un modello termodinamico. Inoltre, l'effetto del pretrattamento di torrefazione è stato studiato attraverso la gassificazione del pellet torrefatto (trattato a due diverse temperature).

Nella prima parte vengono presentate le analisi dei dati elaborati a partire dalla banca dati nazionale e locale (ISTAT Istituto Nazionale di Statistica e Camera di Commercio della Provincia di Bolzano) con l'obiettivo di individuare possibili materie prime alternative per un processo di gassificazione.

Nella seconda parte vengono mostrati i risultati dell'analisi di laboratorio (Laboratorio della Libera Università di Bolzano) sui materiali scelti.

Nella terza parte, i dati ottenuti dalla gassificazione in un gassificatore su piccola scala sono stati elaborati e presentati. L'effetto delle diverse percentuali di corteccia nel cippato è stato studiato con l'obiettivo di valutare la possibilità della sua valorizzazione in un impianto di gassificazione. I risultati dei test di gassificazione sono stati anche impiegati per la calibrazione di un modello utilizzato per la simulazione di gassificazione di un compost fuori specifica (sovvallo) prodotto da un processo combinato di digestione anaerobica e compostaggio.

Infine, è stata effettuata un'analisi economica su possibili applicazioni in impianti di gassificazione su piccola e media scala al fine di valutare la possibilità di una applicazione pratica delle materie prime analizzate (considerando anche il caso di assenza di incentivi).

La valutazione della possibilità di valorizzazione di residui è di primaria importanza non solo per raggiungere standard più elevati in termini di processi "zero waste", ma anche per un futuro sviluppo economico della tecnologia, caratterizzato da un elevato potenziale di sviluppo, ma, allo stato dell'arte, da alti costi di investimento e gestione.

Introduction

By looking for a transition of our world toward a less intensive carbon footprint, renewable energy sources must play a central role in the energy production.

It is nowadays commonly recognized the fact that a gradual reduction in the use of fossil fuels for energy production will give the chance of the creation of a more sustainable energy system.

Renewable energy, as we all know, is often characterized by unpredictability fluctuations which causes problems not only to the final users, but also to the management of the energy distribution.

For this reason, between all the possible environmental resources exploitable by the man, biomass and bioenergy in general could play a fundamental role in a stable and more predictable transition of our energy production. As a matter of fact, the above mentioned concept of sustainability could not be pursued without keeping the focus on environmental footprint, but also basing all the analysis on the economic and social spheres.

Biomass utilization technologies also gives the opportunity of a perfect application of the modern concept of "circular economy", as a matter of fact, before looking at new exploitable resources we have to find the best treatment and useful solution for all those materials coming from our processes.

Human integration with the environment is facing harder challenges every day, thus a mechanism based on the connection between our needs (materials and energy) and our waste products could give a huge chance.

According to Ellen Macartur Foundation, "*Looking beyond the current take-make-waste extractive industrial model, a circular economy aims to redefine growth, focusing on positive society-wide benefits.*"[1]

In Europe this concept have been pursued by means of the directive 2008/98/CE in the field of waste management, sub-products and secondary raw material saying that "*The present directive should help Europe to get closer to a "society of recycling" trying to avoid the production of garbage and use them as resources*". [2]

It has been thus defined the concept of "**End of Waste**", whose starting point is to set the parameters to classify what is a waste and what is a product.

In particular, the European legislation, set the following general criteria to fulfill the "End of Waste" concept:

- The substance/material must be used for common purposes;
- A market/demand regarding the material under analysis already exists;
- The employment of the material do not cause an overall impact on the environment and people.

Waste classification and energy production from waste

In Europe the classification of wastes is based on the European List of Waste introduced by the Commission Decision 2000/532/EC and the Annex III to Directive 2008/98/EC. The LoW (List of Waste, in Italy CER, Catalogo Europeo dei Rifiuti), provides a common path of waste classification with the aim of an easier waste management both for hazardous and not hazardous wastes. The assignment of a LoW code is applied in the entire chain of waste, starting from the production [3].

For what regards the energy recovery from waste products, apart from the common concept of "waste to energy" plants, another thermal treatment is possible.

Part of the municipal solid waste or waste produced by industrial processes or the waste management process can be transformed into a so called SRF (Solid Recovered Fuels), in the Italian nomenclature CSS (Combustibile Solido Secondario). This material is prepared starting from non-hazardous waste with the aim of an energy recovery. The characteristics of this fuel are set by norm EN 15359:2011. A crucial distinction occurs between what can be considered, according to the norm, a waste or a product (according to the Italian nomenclature CSS-Combustibile). Parameters set by the norm EN 15359:2011 are shown in Table 1 [4].

Table 1 Classes and properties (LHV,Cl and Hg content) for the production of RDF (CSS)

Parameters		Classes				
		1	**2**	**3**	**4**	**5**
LHV	MJ/kg as it is	>25	>20	>15	>10	>3
Cl	% dry matter	<0.2	<0.6	<1.0	<1.5	<3
Hg	mg/MJ	<0.02	<0.03	<0.08	<0.15	<0.50

The classes of parameters admitted for the "End of Waste" classification are highlighted in Table 1.

Coming back to environmental goals, European Union have also set fundamental targets known as " 20-20-20 targets" by means of the directive 2009/28/EC trying to reach a share equal to the 20% of the energy production from renewable sources by 2020 [5].

The focus of this work on biomass substrates is justified by IEA forecasts. According to IEA (International Energy agency) in fact, in the period from 2018 to 2023, biomass will be the largest source of growth in the renewable consumptions with an increase of 75,9 Mtoe compared to a production of 460,1 Mtoe, at global level, accounting for the 30% of the growth of the renewables sources exploitation [6].

Overview of the biomass conversion technologies

Most diffuse energy biomass conversion techniques are combustion, pyrolysis and gasification. **Combustion** process can be described as a complete oxidation of the organic matter with the aim of heat production. By decreasing the air content into the reactor to fractions going from 0,15 to 0,3 of the quantity needed for a complete combustion, **gasification** process is achieved, pursuing the production of the so called "syngas", a burnable gas which can be employed as gaseous fuel into ICE (internal combustion engines) or turbines.
Finally, **pyrolysis** is an endothermic process obtained from an heating process in absence of air, in which the organic compounds are partially converted into Gaseous compounds (syngas), partially into liquid hydrocarbons (tars) and also into solids (char) [7].

Gasification processes are not new in the energy production world. Historically, gasification plants have been employed for municipal lighting and cooking purposes. During most of the time in the history, these processes have been fed with coal and peat.
By the 1850 major cities had "gaslight" and after 1880, producer gas started to be used also for power generation.
Interesting applications have been applied subsequently during the World War II to fuel cars with small gasifiers due to gasoline scarcity [8].

A deeper analysis on the theory behind the gasification process, central topic of this thesis, will be given in next chapters.

Possible biomass treatments could also involve biological processes. It is the case of the anaerobic digestion, often coupled/followed by a composting process.
The **anaerobic digestion** process is based on three phases [9]:
- Hydrolysis: bacterial cultures transforms the organic matter (formed by complex polymers) into amino acids, glucose etc.;
- Acidogenesis: acidogenic bacteria degrade the products of the previous step into organic acids, to produce eventually H_2, CO_2 and acetic acid;

- Methanogenesis: products of the previous step ad finally transformed into CH_4 and CO_2 mainly, by means of the action of methanogenic bacteria.

Possible classifications of the processes are performed:
- According to the percentage of dry matter the process can be classified as **humid** (humidity>90%), **dry** (humidity<80%) or semi-dry in between;
- According to the structure subdivision of the reactor the process can be based on a **single-stage** (the three phases of the process occur in the same reactor) or **double-stage** (in a first step hydrolysis and organic acid formation in performed and methanogenesis occurs in a second stage);
- Depending on the material feed method in the reactor, a **continuous** flow or a **batch** flow (the digester is filled at the beginning and emptied just when the "complete" digestion ends) can be employed. It must be highlighted the fact that digestion, occurring thanks to the volatile consumption in the biomass, is never complete, but it is stopped when 95% of the biogas production at infinite time is reached.
- According to the mixing process a **full-mixing** or a **plug-flow** is obtained (note that in the second case the material flows thanks to a piston through the different phases of the process);
- Depending on the temperature employed, a **mesophilic** (temperature in the range 32-37°C) or **thermophilic** (temperature around 55°C) can be distinguished.

Overview of the biomass pretreatment processes

As already said, between all the renewable sources, biomass can guarantee a stable and predictable energy source, but its nature can present a huge variability considering different species or cultivation/growing region.
For these reasons, especially if we want to consider the use of waste biomasses and materials affected by high variability, pretreatments could give the chance to have more stable and uniform characteristics (i.e. moisture content, low heating value, density, energy density). Possible pretreatment processes involve a size reduction (chipping and pelleting) or a thermal process (drying and torrefaction).

Considering forestry residues such as branches or barks, wood **chipping** is a possible pretreatment process, allowing an easier transportation and storage.
Wood chipping gained importance in last decades for the possibility of valorization and exploitation of biomass feedstocks which would be otherwise not used [10].

The production of this material is performed thanks to specific machines, which can be subdivided, according to the employed geometry of the cutting tool, into [10]:

- **Disk** machines: knifes are amounted on a central tool and the presence of a moving counter structure allows to produce wood chips of variable dimension from 0.4 to 4.5 cm;
- **Drum** machines: this geometry allows the treatment of pieces of lager dimensions, but producing a more heterogeneous product. Cutting knifes are mounted tangentially on a central drum and produced woodchips can reach dimension of 6.5 cm;
- **Screw** machines: a reducing section screw with cutting angles is employed as cutting tool. This machines are used just for the treatment of entire logs, producing chips of big dimensions (up to 8 cm);

Woodchips machines are usually built in three different power ranges: small, medium and high, characterized by powers ranges of <50 kW, 50-110 kW and <130 kW respectively.

The second size reduction process is **pelleting**. This process consists in a densification of a fine woody matter (i.e. sawdust) by means of the application of an extrusion process. In particular, the raw material is fed into rotating drums, where the action of rollers produces the required pressure needed to force the material into dies (forming the material obtaining a cylindrical shape).

The aim of the pelleting process are: the energy and mass densification of a raw material, the easier and more reliable storage (pellets are in fact characterized by a uniform shape and a smaller humidity content if compared with wood logs or woodchips) [11].

Density of a fuel affects the transport methodology, its related cost and the storage needing [12]. Table 2 shows how the same material can be highly densified by means of a pelleting process reaching in some case an increase in density equal to 3.5 times.

Table 2 Densities (at a moisture content of 15%) of various biomasses (kg/m3) (Kicherer 1996 Hartmann and Strehler 1995) [12]

Biomass	Density		Bulk density	
	Large-size cubic bales	Round bales	Chaff	Pellets
Herbaceous biomass:				
Straw	150	120	70	520
Miscanthus	130		120	
Whole cereal plants	220	190	130	560

Another crucial parameter related to biomasses is the energy density. In Table 3 it can be seen how the physical form in which biomass is used drastically influence this parameter.

Table 3 Energy density of different biomass in different biomass forms [12]

Fuel	Density ρ [kg/m^3]	Lower heating value (LHV) [MJ/kg]	Energy density [GJ/m^3]
Straw, large-size cubic bales	150	14.4	2.2
Straw, chaff	70	14.4	1.0
Straw, pellets	520	14.4	7.5
Whole plant, large-size cubic bales	220	14.4	3.2
Miscanthus, large-size cubic bales	130	14.4	1.9
Wood chips	250	15.3	3.8
Hard coal	870	28	24.4
Brown coal	740	10	7.4

For what regards thermal pretreatments, the **drying process** consists in the reduction of the moisture content of a raw feedstock by means of an heating process (note that a gross reduction of the moisture content can be also obtained by means of a forced ventilation into the closed biomass storage site).

The process is usually performed employing heated air feeding to enhance the drying effect. The employed structures for this purpose are based on the presence of a double flooring below the biomass feedstock. The presence of holes into the double flooring allows the passage of the heated air (whose temperature increase can be achieved by means of the passage through heated boundless tubes) [10].

The second cited thermal pretreatment (**torrefaction**), is based on a "soft pyrolysis" performed at a temperature between 230 and 300°C in absence of a oxidizer agent. The aim of this process are the increase of the energy density, the reduction of the oxygen to carbon ratio (O/C) and of its hygroscopic behavior. During the process both H_2O and CO_2 are removed (causing most of the weight loss), thus an decrease of O/C and H/C ratios are obtained contemporarily. As a consequence, the relative carbon content increases and the over oxidation caused by the high content of oxygen in the non-treated biomass could be reduced during a gasification process.

The results and gains in biomass properties depend of course on the temperature of the process, duration and feedstock.

Another consequence of the process is the modification of the physical structure of the biomass obtaining a more friable material as a result of the depolymerization of the hemicellulose [13].

This different structural behavior creates, from one side a reduction of the energy needed for a size reduction of the material, but on the other hand, a secondary mass loss have been detected in the case of torrefied pellets (the first loss is produced by the loss of part of volatiles during the process). In particular, part

of the material is lost in the form of a fine and not recoverable (for the plant purposes) powder. Experimental measurements showing this weight loss will be shown in chapter 2.

Trying to focus on the torrefaction mechanism it is important to start from the structural composition of the biomass.

Two of the three main constituents of the biomass (cellulose, hemicellulose and lignin) act as cement and steel rods respectively in a reinforced concrete.

In particular, cellulose is supported by hemicellulose (which acts as the concrete), thus its depolymerization helps in achieving an easier size reduction. The hemicellulose decomposition occurs in the temperature range between 150 and 280°C (this temperature range is in fact adopted as torrefaction temperature range and hemicellulose decomposition is the primary mechanism of the process).

A successive easier densification is also helped by the softening of the lignin (the binder component of the biomass) which reaches its softening temperature already at 130 °C.

As mentioned, the most important parameters of torrefaction are time and temperature of the process. Usually torrefaction temperature is reached slowly and held for some period.

According to Eq. i.1 general design rules suggests heating rates of [13]:

$$\frac{\theta_{torr}-200}{t_{heating}} < 1° \frac{C}{s} \qquad (i.1)$$

Where θ_{torr} is the torrefaction temperature, practically chosen between 200 and 300 °C and $t_{heating}$ is the time for which the temperature is held above 200 °C (usually equal to 30 minutes) [13].

The results of the general characterization of the torrefied material will be shown in next chapters.

Chapter 1

1.1 Identification of possible residual feedstocks for gasification purposes

In this chapter an analysis of the residual feedstocks, performed at national level, will be presented.

The aim of the analysis is to identify, in a first step, the major residual biomasses and starting from those data to analyze the possibility of a local application for the chosen technology (gasification process).

The analyzed materials belongs to a macro category of ligno-cellulosic based matter but can be divided into three different natures:

- Agricultural residues;
- Forestry industry chain residues (bark);
- Materials treated into anaerobic digestion plants as structural component, separated by screening/sieving.

The treatment of the last mentioned material represents a cost for waste management plants. The others are instead often disposed directly on the land or not processed at all for economic reasons.

1.2 Agricultural residues

1.2.1 Applied methodology and results

The estimation of the data relative to the biomass residuals availability have been performed, for the woody agricultural residues, starting from national databases made available from ISTAT (Istituto Nazionale di Statistica) [14]. National databases present the cultivated surface for the different crops for each region. This data have than been used to compute the availability of residues by means of the application of factors expressing the production of pruning residues in $tons_{pruning/residue}$ per hectare of cultivated land (data of 2018).

Apple trees and grapevine cultivations are the most representative and spread in Trentino-Alto Adige region. Grapevine together with other cultivations such as peach and pear are instead more representative if North Italy in general is considered. Finally, Citrus and Olive trees are mostly concentrated in South Italy.

The amount of residues produced during the year have been computed according to the factors shown in Table 4 [15-20].

Table 4 Residues production factors employed for the calculation of yearly productions of residues

	Pruning residues [t/ha]	Humidity [%]
Grapevine	2.0	50
Olive tree	2.0	35
Citrus tree	1.2	40
Apple tree		
Trentino-Alto Adige	4.2	44
Other regions	2.4	44
Pear tree	1.7	40
Peach tree	2.6	40

Table 4 shows pruning residues quantity per unit of cultivated surface at national level. It is worth mentioning that apple trees pruning presents a much higher value in Trentino-Alto Adige region if compared to the average national value. This phenomenon is justified by the more intensive cultivation achieved for this particular crop [19].

The following Tables present the data relative to the abovementioned cultivations. Table 5 shows the cultivated surface and the computed quantity of pruning residues on as received and dry base.

Table 5 Apple trees and grapevine cultivated areas and pruning residues on wet and dry base

	Apple trees			**Grapevine**		
	S [ha]	Pruning residues [kt/year]	Pruning residues (dry matter) [kt/year]	S [ha]	Pruning residues [kt/year]	Pruning residues (dry matter) [kt/year]
Piemonte	6144	14.7	8.3	41584	83.2	41.6
Valle d'Aosta	280	0.7	0.4	470	0.9	0.5
Lombardia	1569	3.8	2.1	24636	49.3	24.6
Liguria	62	0.1	0.1	1624	3.2	1.6
Trentino-Alto Adige	27520	115.6	64.7	15055	30.1	15.1
Veneto	5842	14.0	7.9	87027	174.1	87.0
Friuli-Venezia Giulia	1246	3.0	1.7	23040	46.1	23.0

Emilia-Romagna	4479	10.7	6.0	49775	99.6	49.8
Toscana	831	2.0	1.1	54609	109.2	54.6
Umbria	233	0.6	0.3	11911	23.8	11.9
Marche	199	0.5	0.3	15171	30.3	15.2
Lazio	455	1.1	0.6	20858	41.7	20.9
Abruzzo	554	1.3	0.7	32867	65.7	32.9
Molise	290	0.7	0.4	5600	11.2	5.6
Campania	3375	8.1	4.5	24674	49.3	24.7
Puglia	245	0.6	0.3	109785	219.6	109.8
Basilicata	401	1.0	0.5	2458	4.9	2.5
Calabria	512	1.2	0.7	9057	18.1	9.1
Sicilia	685	1.6	0.9	119995	240.0	120.0
Sardegna	205	0.5	0.3	27270	54.5	27.3
Italy	55127	181.8	101.8	677466	1354.9	677.5

Table 5 shows how highest residue production can be detected, for the apple pruning, in Piemonte and Trentino Alto-Adige region (for which the production belongs to another order of magnitude).

Grapevine residues are instead more spread in the entire country due to the historical culture and the huge market linked to wine production. At national level, the grapevine pruning are much more available, but considering the peculiar case of Trentino Alto-Adige region, apple pruning are characterized by a not negligible availability.

A focus on province level for Trentino-Alto Adige region for apple trees is reported on Table 6.

Table 6 Apple trees and grapevine cultivated areas and pruning residues on wet and dry base for Trentino Alto-Adige region

	Apple trees		
	S [ha]	Pruning residues [kt/year]	Pruning residues (dry matter) [kt/year]
Bolzano/Bozen	17760	74.6	41.8
Trento	9760	41.0	23.0

Table 6 shows how the production is not equally distributed in the entire region, but instead roughly the 64% of the production is concentrated in Bolzano province.

The period of availability, according to the natural cycle of the plant and production needs, are shown in Table 7.

Table 7 Apple trees and grapevine availability periods [20]

	Period of availability
Grapevine	January-May
Apple tree	January-February

Pruning activity is concentrated in short periods during the year for apple threes, thus the needing of seasonal storages would be needed in order to consider the energy valorization of these residues. Grapevine pruning season is instead much longer.

The results of the analysis for pear and peach trees are reported in Table 8.

Table 8 Pear and peach trees cultivated areas and pruning residues on wet and dry base

	Pear tree			**Peach tree**		
	S [ha]	Pruning residues [kt/year]	Pruning residues (dry matter) [kt/year]	S [ha]	Pruning residues [kt/year]	Pruning residues (dry matter) [kt/year]
Piemonte	1310	2.2	1.2	3871	10.1	5.6
Valle d'Aosta	10	0.0	0.0	0	0.0	0.0
Lombardia	758	1.3	0.7	345	0.9	0.5
Liguria	17	0.0	0.0	121	0.3	0.2
Trentino-Alto Adige	37	0.1	0.0	6	0.0	0.0
Veneto	2957	5.0	2.8	2020	5.3	2.9
Friuli-Venezia Giulia	155	0.3	0.1	190	0.5	0.3
Emilia-Romagna	18104	30.8	17.2	11036	28.7	16.1
Toscana	439	0.7	0.4	568	1.5	0.8
Umbria	82	0.1	0.1	138	0.4	0.2
Marche	60	0.1	0.1	774	2.0	1.1
Lazio	207	0.4	0.2	1886	4.9	2.7
Abruzzo	154	0.3	0.1	6335	16.5	9.2
Molise	110	0.2	0.1	305	0.8	0.4
Campania	732	1.2	0.7	19540	50.8	28.5
Puglia	389	0.7	0.4	4000	10.4	5.8
Basilicata	409	0.7	0.4	2882	7.5	4.2
Calabria	293	0.5	0.3	2814	7.3	4.1
Sicilia	3316	5.6	3.2	6806	17.7	9.9
Sardegna	77	0.1	0.1	2262	5.9	3.3
Italy	29616	50.3	28.2	65899	171.3	95.9

The period of availability in the case of pear and peach three is reported in Table 9.

Table 9 Pear and peach trees availability periods [20]

	Period of availability
Pear tree	January-February
Peach tree	February-April

A longer period of availability can be noticed in the case of peach three if compared with apple and pear pruning. It is noticeable that the annual production of pruning on dry base for pear three is much smaller respect peach, apple and grapevine.

The results of the analysis for citrus and olive trees are shown in Table 10.

Table 10 Citrus and olive trees cultivated areas and pruning residues on wet and dry base

	Citrus trees			**Olive tree**		
	S [ha]	Pruning residues [kt/year]	Pruning residues (dry matter) [kt/year]	S [ha]	Pruning residues [kt/year]	Pruning residues (dry matter) [kt/year]
Piemonte	0	0.0	0.0	127	0.2	0.2
Valle d'Aosta	0	0.0	0.0	0	0.0	0.0
Lombardia	0	0.0	0.0	2423	4.7	4.7
Liguria	32	0.0	0.0	15940	31.2	31.2
Trentino-Alto Adige	0	0.0	0.0	387	0.8	0.8
Veneto	0	0.0	0.0	5113	10.0	10.0
Friuli-Venezia Giulia	0	0.0	0.0	427	0.8	0.8
Emilia-Romagna	0	0.0	0.0	3534	6.9	6.9
Toscana	19	0.0	0.0	83168	163.0	163.0
Umbria	0	0.0	0.0	25300	49.6	49.6
Marche	0	0.0	0.0	9018	17.7	17.7
Lazio	547	0.7	0.4	80181	157.2	157.2
Abruzzo	7	0.0	0.0	41548	81.4	81.4
Molise	4	0.0	0.0	15360	30.1	30.1
Campania	2934	3.5	2.0	75480	147.9	147.9
Puglia	9350	11.2	6.3	379340	743.5	743.5
Basilicata	5655	6.8	3.8	27470	53.8	53.8
Calabria	35691	42.8	24.0	336400	659.3	659.3
Sicilia	77731	93.3	52.2	157092	307.9	307.9
Sardegna	4889	5.9	3.3	38804	76.1	76.1
Italy	136859	164.2	92.0	1297112	2542.3	2542.3

It is worth mentioning the fact that olive tree pruning seems to be the most available at national level with a national global production of 2542.3 kt each year. Citrus tree pruning residues are comparable with apple and peach residues,

but also in this case a concentration in few regions (Calabria and Sicilia) can be noticed.

Pruning residues for citrus and olive trees availability periods are shown in Table 11.

Table 11 Citrus and olive trees availability periods [20]

	Period of availability
Olive tree	Jen-Apr, Oct-Dic
Citrus tree	May-August

Also the period of availability seems to be more spread during the year for olive trees respect all the other species, while citrus residues availability is concentrated in summer months.

Finally, it must be specified the fact that currently, the disposal of all the above mentioned pruning residual occurs by means of grinding and direct land disposal or in other case direct combustion on field [20].

1.3 Forestry industry chain residues (bark)

1.3.1 Local industry characteristics

Considering the sawmill and timber production industry, in northern Italy, the average size of these companies is usually small.

This means that sawmills usually process less than 5000 m^3 of wood per year. A small percentage of companies in the sector are much larger, processing up to 3.5 10^4 m^3 of wood [21].

1.3.2 Applied methodology and results

Data relative to the availability of bark have been computed following a different procedure if compared with the previous materials.

Basing on the methodology of global quantities estimation proposed by Emer et al and Prando et al. [21,22], the annual volume of timber traded in the local market has been estimated. According to Emer et al. [21] the specie considered for the global estimation is Spruce (Picea Abies), being the most representative for the trades of the zone and the average density considered for the calculation is 450 kg/m3 .

The average trade price for the year 2017 has been found to be 106 €/m3 [23]. The annual turnover (for year 2017) in euro has been derived from the data directly provided by the Chamber of Commerce of the province of Bozen [24].

The trade price has been used to compute the global quantity according to the Eq. 1.1:

$$Total\ Volume\ traded = \frac{Annual\ turnover\ in\ €}{Trade\ price\ in\frac{€}{m^3}} \qquad (1.1)$$

Eq.1.1 is applied for each of the timber flow trade (import, export) allowing the computation of their relative volumes expressed on annual base (the local production quantity can instead be accessed from ISTAT database).

The annual masses produced locally, imported and exported are than computed by means of the multiplication of the volumes found before for the average representative density of 450 kg/m³ [21].

The results of the trade analysis are reported in Table 12.

Table 12 Annual productio, import and export of the timber in Trentino Alto-Adige region (2018)

Alto Adige timber trades	
	[kt/year]
Timber from local production	179.3
Import	24.9
Export	22.6
Processed timber	181.7

Starting from the annual volume of processed timber computed according to Eq.1.2:

$$Processed\ timber = Timber\ from\ local\ production + import - export\ (1.2)$$

it is possible to access the quantity of bark produced in the region by applying a conversion coefficient equal to 0.13 m³$_{bark}$/ m³ $_{round\text{-}wood}$ [25].

Starting form an annual quantity of processed timber of 181.7 kt (corresponding to 403777.8 m³ of round wood) it is possible to estimate the yearly production of bark into approximatively 52500 m³ of solid bark (corresponding to 23.6 kt considering a bulk density equal to 180 kg/m³ and a volume occupied by the biomass in form of chips starting from solid wood in a ratio of 2.5:1 [10]).

1.4 Materials treated into anaerobic digestion plants as structural component, separated by screening/sieving

Another residue considered for the energy valorization is the compost out of specification obtained from the OFMSW (organic fraction of municipal solid waste) management into anaerobic digestion plants (coupled with a composting phase for the produced digestate coming from the anaerobic phase). The consideration of this material is based on the presence of a noticeable quantity of biomass (wood) into the material. The woody biomass presence is due to the utilization/treatment of the maintenance products coming from public parks and gardens (grass, branches etc.) as structural component during the composting phase (the process consists in fact into an aerobic oxidation of the volatile fraction of the digestate, thus a structural component is needed to ensure a sufficient porosity of the mass).

With the aim of a better comprehension of the nature of the abovementioned material, a list of the possible steps of the combined process of anaerobic digestion of the OFMSW and post-composting of the mix formed by the digestate (produced by the anaerobic digestion phase) and the green maintenance products is proposed:

- Collection of the organic fraction of municipal solid wastes;
- Material shredding;
- Screening and transportation into the anaerobic digestor;
- Temporary accumulation and partial recirculation;
- Mixing with pruning, leaves etc coming from public and private garden maintenance;
- Stabilization by means of air insufflation with the aim of volatiles oxidation;
- Intermediate screening with recirculation into the mixing tank;
- Final composting maturation;
- Final sieving.

Fig.1 shows a brief and schematic flowchart of the of the steps/processes listed above. The material under investigation is the compost out of specification obtained from the last sieving procedure highlighted in Fig.1 as "OVER-SIEVE FRACTION".

Figure 1 Flowchart representing the combined process of anaerobic digestion and composting, producing the material under investigation (compost out of specification)

1.4.1 Applied methodology and results

A first analysis proposed has been referred to a specific processes employed in the waste management sector (*Bio Energia Trentino Srl* placed in Cadino).
This material described in section 1.4 is actually characterized, according to the European legislation with the CER code 19 05 03 (thus as "compost out of specification") and currently disposed in landfill where it is used as daily coverage.

A direct communication with the local waste management plants allowed to estimate the annual production, for the single plant, of this material in 5000 t/year. A fraction equal 1500 t/year (quantity under investigation in this work) has to be disposed at a cost of 50 €/t (producing an annual cost for the plant equal to 75000 €), while the other part is recirculated as structural component in the maturation process.
It must be highlighted the fact that the quantity of material is referred to an annual treated quantity of green fraction equal to 8500 t/anno and the first process (anaerobic digestion) is a semi-dry process, processing 25715 t/year of OFMSW.
It can be noticed how the quantity under analysis produced each year, that must be disposed, corresponds to the 4.4% of the total input of the plant (OFMSW+ green fraction).

Considering the same percentage (4,4%) for a national analysis and starting from the following data [26]:
- Quantity of treated MSW equal to 440 kg/year per capita;
- Percentage of MSW treated in anaerobic digestion and composting plants equal to 19%;

- Population of 60.59 million people;

it is possible to estimate the quantity of MSW treated with anaerobic digestion and composting processes in 5065 kt/year and a production of compost out of specification of 221.9 kt/year. It is worth mentioning the fact that 18 kt (of the 221.9) are, at the state of the art, exported in Hungary.

Notice that the combination of anaerobic digestion and composting and technologies employed at national level could be different from the one employed in the waste management considered in the analysis (*Bio Energia Trentino* plant), thus the annual quantity of material to be disposed indicated at national represents an estimation.

Chapter 2

Feedstock characterization

The characteristics of the biomass samples have been found by means of the measurement of:

- moisture content of the samples (as received and after the stabilization process);
- ash content (of the stabilized samples);
- HHV and LHV high heating value;
- C,H,N,S content with the aim of an elemental analysis;
- Mass loss against temperature by means of a thermogravimetric analysis;

2.1 Samples description

2.1.1 Material employed as reference for the gasification tests: high quality woodchip

An high quality wood chip sample has been considered as reference for the gasification tests.

The high quality wood chips samples to be used in the gasification plant have been collected from the company *Furlan Luigi & Figli* placed in Mezzocorona (TN). At the moment of the collection, woodchip where collected in piles placed inside a closed warehouse. A sample of this material is shown in Fig.2.

Figure 2 Samples of the high quality woodchip and the barks

A first comparison has been performed in order to detect the differences between an high quality woodchip and a low quality one (forestry woodchip). A graphical comparison between the high quality and low quality woodchip is proposed in Fig.3.

Figure 3 On the left a forestry woodchip, on the right an higher quality woodchip

By comparing the high and low quality woodchips, a different quantity of small branches, pine needles and bark have been noticed.

According to normative ISO 17225-4, considering the moisture content (M25, thus moisture as received <25%), ash content (A1.0, thus ash content on dry base smaller then 1%), the chosen woodchip (high quality one) could be classified as an A1 class.

Note that the normative ISO 17225-4, concerned with woodchip quality imposes range of acceptability just for moisture content, dimensions and ash content. In order to study the effect of barks during gasification, also the bark content in weight have been measured in the two different woodchip samples.

Table 13 shows the results of the global characterization obtained for the high quality woodchip.

Table 13 Mass percentage of fine fraction (smaller than 4mm) and bark presence for the high quality woodchip

Woodchip global characterization	
< 4mm	3%
Bark	8%

It must be highlighted the fact that the low quality (forestry) woodchip presented an average bark quantity of 15% in mass.

2.1.2 Forestry residues: barks and sawdust

The first residual material considered has been barks and sawdust (the second material is not really a residue since it is easily valorized and sold by sawmills, but it has been analyzed as benchmark case for a direct comparison between wood and bark).

Sawdust and the first bark sample have been obtained from a local sawmill (*TAZT OHG* des TAZT FLORIAN & Co.). The company use to collect the sawdust into bags of roughly 20 kg each, instead barks are collected into piles exposed to atmospheric conditions. According to the owner of the company, bark piles are emptied every 3-4 months, thus the material is supposed to be no older than that.

The second bark sample has been collected from the same company producing the high quality woodchip (*Furlan Luigi & Figli* placed in Mezzocorona (TN)). Also in this case barks were collected into piles exposed to atmospheric conditions. Fig.4 shows the samples once collected.

Figure 4 Sawdust and bark samples once collected

2.1.3 Over sieve residual material: Compost out of specification

The second residual material considered in this work is the compost out of specification coming from waste management plants. As explained in Chapter 1, the material is the result of the last screening/sieving downstream the composting process (in which the digestate produced by the anaerobic digestion phase of the OFMSW is mixed with the green garden maintenance material, which acts as structural component). The material has been sampled in the waste management plant *Bio Energia Trentino Srl* placed in Cadino.

Fig.5 shows a sample of the compost out of specification under investigation:

Figure 5 Material separated by screening/sieving

The presence of inert material of big dimension and of a plastic fraction can be clearly noticed. The presence of these fractions is probably justified by the collection methods of the public gardens maintenance material, which is partially collected from the ground (where external materials are often already present).

For this material, a first macro product analysis have been performed in order to individuate the main fractions of the sample, dividing:
- Ligno-cellulosic material of bigger size;
- Plastic fraction;
- Inert fractions (small stones and glass pieces);
- Fine woody part and dusty material;

The relative mass of each fraction is reported in Table 14.

Table 14 Weight percentage of each macro-fraction of the compost out of specification

	Weight percentage in the material
%wt, plastic	3%
%wt, inert	23%
%wt, ligno-cellulosic	63%
%wt, fine-dusty-not-identifiable	11%
	100%

With the purpose of an energy valorization, different mix of samples have been separated, in order to detect the best configuration to be used for an eventual gasification process:

- Ligno-cellulosic material of binger size + Plastic fraction (mix);
- Ligno-cellulosic material of binger size without plastic;
- Plastic fraction;
- Fine woody part and dusty material.

2.1.4 Samples employed for the torrefaction pretreatment consideration: pellet and torrefied pellet

As explained, the torrefaction pretreatment has been considered as possible option with the aim of improvement of a residual biomass characteristics. For this reason, samples of pellet and torrefied pellets at two different torrefaction temperature (250 °C and 270°C) have been analyzed. Fig. 6 clearly shows the typical optical effect of torrefaction process.
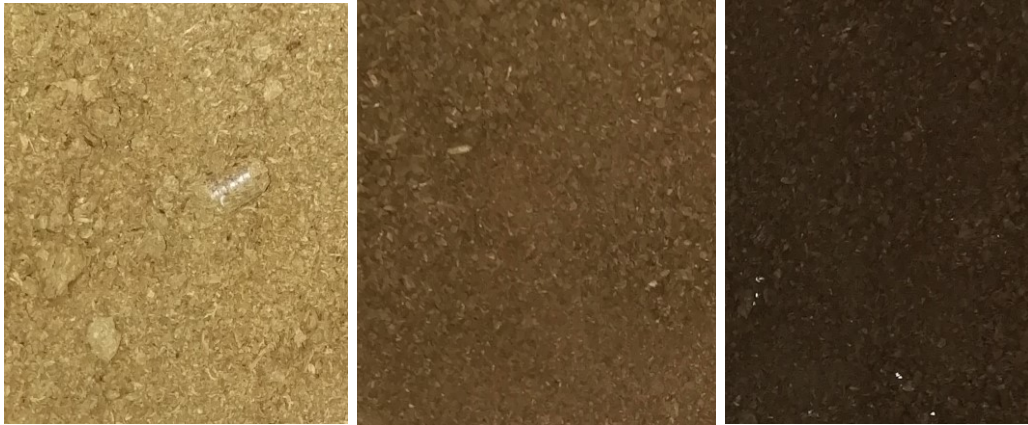

Figure 6 In order from left to right, grinded samples of: standard pellet, torrefied pellet (at 250°C) and torrefied pellet (at 270°C)

2.2 Samples pretreatment

The nature and the state of the samples are different, thus pretreatments have been required in order to manage the different laboratory analysis.
The first step have been a stabilization process by means of keeping the samples in a muffle furnace (*Nabertherm GmbH L 15/11/B410, Figs.7*) at 50 °C for 48 h.

Figure 7 Picture of the muffle furnace used for the stabilization process and its technical specifications

Due to the bigger sizing, the stabilized bark sample has been milled into a cutting mill (*Pulverisette 19, Fritsch, Fig.8*).

Figure 8 Cutting mill used for the bark pretreatment

2.3 Proximate analysis

Proximate analysis express the biomass composition in terms of its main constituents such as [13]:

- Moisture;
- Volatile matter;
- Ash;
- Fixed carbon;

2.3.1 Moisture content

Moisture content is a crucial parameter to analyze, given its strong influence on the energy content of a biomass. Considering biomasses, both ligno-cellulosic and straws, the moisture content could affect the LHV (low heating value), more than the type of biomass it selves [12]. The just mentioned phenomenon is shown in Fig.9.
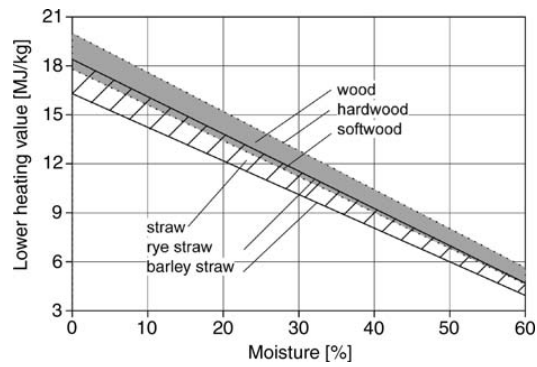
Figure 9 Influence of moisture content on LHV [12]

Water content is determined by placing the samples into an oven at a temperature of 105°C for 24 h. The employed oven and containers for the moisture measurement are shown in Fig 10.
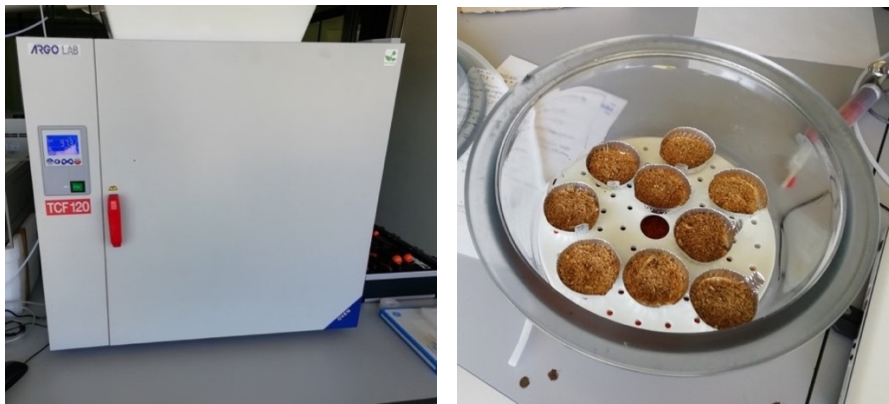
Figure 10 Oven used for the moisture content derivation and dried samples

According with the standard UNI EN 14774-2:2009 [27], the moisture content can be derived (by means of weighting the sample before and after the drying process) on weight base as:

$$M\% = \frac{(wt_{,gr,wet} - wt_{,gr,dry})}{(wt_{,gr,wet} - wt_{cont})} \, 100 \qquad (2.1)$$

where:
$wt_{,gr,wet}$ is the gross weight of the sample in g (comprehensive of the drying container)
$wt_{,gr,dry}$ is the gross weight of the sample in g after the drying process
wt_{cont} is the weight in g of the drying container

Moisture content can be measured on the sample as received, or on the stabilized material.

2.3.2 Ash content

Ash represents the solid inorganic residue remaining after the complete combustion of the fuel. Its primary constituents are usually silica, aluminum, iron and calcium. Even smaller amounts of titanium, magnesium, sodium and potassium may also be present [13].

The ash content may play a significant role in the utilization of biomass feedstocks, especially if alkali or halides such as potassium or chlorine respectively. It must be highlighted the fact that, as noticed for the material coming from the waste management plant, the ash obtained from the thermal conversion does not necessarily come from the biomass itself, but also collection and storage operations could cause the link to inert materials [13].

The ash content is determined according to norm EN 14775:2009 [28] which prescribes the following heating conditions:

- Rise the furnace temperature to a temperature of 250°C over a period between 30 and 50 min, maintaining it for 60 minutes (this process allows the release of the volatiles before the ignition);
- Rise the furnace temperature evenly to a temperature of 550 °C over a period of 30 minutes to keep it constant for 120 min.
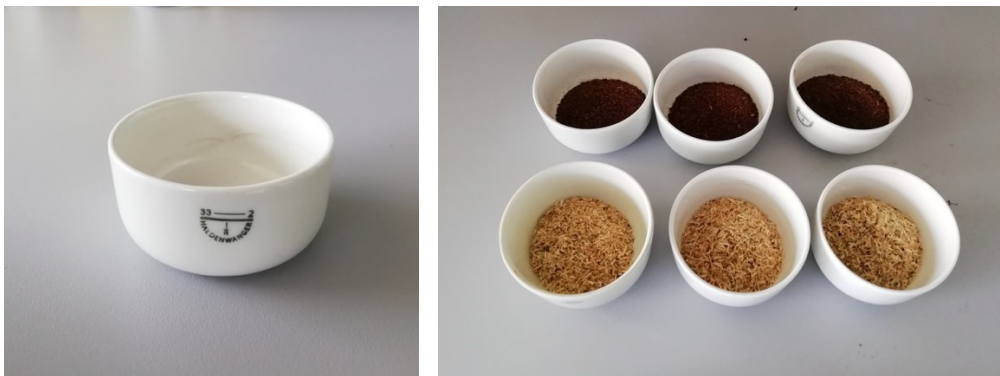
Figure 11 Ceramic container ese for the ash content determination into the muffle furnace and

dry samples before the process

In Fig.11 it can be noticed how this characterization test is performed using certified inert (according to the norm porcelain, silica or platinum) containers.

The result of the test (remaining ashes) for the bark and woodchip samples are shown in Fig.12.

Figure 12 Ash of the woodchip and bark samples

Ash content is calculated according with Eq. 2.2:

$$Ash = 1 - \frac{wt_{gross,before} - wt_{gross,after}}{wt_{gross,before} - wt_{container}} \qquad (2.2)$$

where:

$wt_{gross,before}$ is the weight of the gross sample before the heating process in the furnace muffle [g];

$wt_{gross,after}$ is the weight of the gross sample after the heating process [g];

$wt_{container}$ is the weight of the inert container (tare) [g];

2.4 Elemental analysis

The elemental characterization allows to express the biomass composition in terms of carbon (C), hydrogen (H), nitrogen (N), Sulphur (S), oxygen (O), ash and moisture.

The oxygen content in weight percentage is not measured in this case but calculated by difference according with Eq. 2.3 on dry base:

$$O = 1 - Ash - C - H - N - S \qquad (2.3)$$

The test is performed according to the norm UNI EN 15104:2004 and employing the Elementar Vario MACRO Cube analyzer (in Fig. 13).

Figure 13 Vario MACRO Cube employed for the elemental analysis and an upper view of the charging disc

2.5 Calorimetry

The determination of the HHV (high heating value) is performed by means of the use of a colorimetric bomb, thus performing a combustion process in large excess of oxygen under pressure in a closed chamber.
The test is based on the prescriptions of the norm UNI EN 14918:2010 and the equipment employed is a IKA C200 (in Fig. 14).

Figure 14 Calorimetric bomb IKA C200

After the sample preparation (stabilized conditions), by means of weighting inside a certified plastic bag and placing it into a glass crucible, the vessel in filled with pure oxygen at a pressure of 40 bar. The software implemented in the equipment, logs the temperature increase of the water placed in the container and compute the HHV of the sample by means of an energy balance of the system, according with Eq. 2.4:

$$HHV = \frac{C \Delta T - Q_{ext,1} - Q_{ext,2}}{m_{sample}} \quad (2.4)$$

where:

C is the heating capacity of the system [J/K]

ΔT is the temperature difference of the water detected during the process [K]

$Q_{ext,1}$ is the heat generated by the cotton thread employed for the sample ignition [J]

$Q_{ext,2}$ is the heat generated by the plastic bag [J]

m_{sample} is net mass of the sample [g]

HHV is the higher heating value of the sample computed by the equipment [J/g]

Data to be inserted for the calculations performed by the software are the net mass of the sample and the mass of plastic bag (to compute $Q_{ext,2}$).

Starting from the HHV in stabilized conditions, it is possible to refer the same value to the dry conditions (optaining the HHV_dry) and the lower heating value in dry conditions (LHV_dry) by means of the equations:

$$HHV_{dry} = \frac{HHV}{(1-M_{stabilized})} \qquad (2.5)$$

$$LHV_{dry} = HHV_{dry} - h_{lat}\, \frac{g_{H_2O,products}}{gH_2}\, \frac{H}{100} \qquad (2.6)$$

where:

$M_{stabilized}$ is the moisture of the stabilized sample

h_{lat} is the vaporization heat of water assumed equal to 2.443 [J/g]

H is the hydrogen content of the sample on dry base

$\frac{g_{H_2O,products}}{gH_2}$ express the ratio of the mass of water produced per unit of hydrogen content and it is equal to 8.936

2.6 Thermogravimetric analysis

This test consists in a mass measurement over time while temperature increases. The test has been performed in an inert atmosphere (N_2) (simulating a pyrolysis test). The aim of the test, performed on the bark sample (1) was the possibility to understand the behavior of this feedstock in the temperature range of the gasification process. In particular, the ash melting behavior must be taken into account. An example of possible equipment needed for the test is shown in Fig.15.

Figure 15 Thermal apparel employed for the tg analysis [29]

2.7 Characterization results

2.7.1 Material employed as reference for the gasification tests and Forestry residues: high quality woodchip, barks and sawdust

In these paragraphs the results of the characterization of the chosen materials are reported. The elemental characterization results for the woodchip, sawdust, and bark samples are reported in Table 15.

Table 15 Results of the characterization for bark, sawdust, woodchips and barks employed in the gasification tests samples expressed as: average value standard deviation

		Wood chips	Sawdust	Bark(1)	Bark(2) (gasification)
moisture	%wb	3.19 ± 0.14	3.21 ± 0.01	4.05 ± 0.04	2.91 ± 0.1
ash	%db	0.69 ± 0.03	0.5 ± 0.08	14.38 ± 1.09	4.04 ± 0.02
C	%db	49.19 ± 0.27	50.51 ± 0.14	50.66 ± 0.59	50.3 ± 0.23
H	%db	6.2 ± 0.07	6.57 ± 0.08	5.85 ± 0.06	5.64 ± 0.02
O	%db	43.58 ± 0.28	42.04 ± 0.11	28.02 ± 1.31	39.47 ± 0.18
N	%db	0.12 ± 0.01	0.18 ± 0.06	0.37 ± 0.05	0.35 ± 0.01
S	%db	0.23 ± 0.01	0.21 ± 0.07	0.11 ± 0.01	0.2 ± 0.02
HHV_{dry}	MJ/kg	19.57 ± 0.02	19.14 ± 0.92	17.24 ± 0.41	19.70 ± 0.13
LHV_{dry}	MJ/kg	18.22 ± 0.02	17.72 ±0.92	15.96 ± 0.41	18.47 ± 0.13
HHV_{Milne}	MJ/kg	19.73	20.85	20.52	19.78
LHV_{Milne}	MJ/kg	18.38	19.42	19.19	18.55

(1) From company *TAZT OHG* des TAZT FLORIAN & Co.
(2) From company *Furlan Luigi & Figli* placed in Mezzocorona (TN)

Note that values are expressed in table as the average of three test ± the standard deviation.

This first bark sample (1) presents a high value of ashes if compared to sawdust, woodchip and also the second bark sample (2). On the contrary, the other characteristics of the composition seem to be comparable. The high value detected could be due to the storage technique (possibility of dust collection) or to the volatile fraction consumption due to aging (according to AIEL, the annual loss of dry matter in percentage can range from 2 to 22% due to an exposed storage of the biomass).

The bark sample (2) employed in the gasification tests presents instead an ash content which is higher than the reference material (woodchip), but the increase is not as high as in the case of bark (1). Moreover, the high carbon content and the small oxygen content of the bark sample (2) are responsible for an heating value that is, on dry base, slightly higher than the woodchip.

2.7.1.1 Thermogravimetric analysis result (on the bark sample)

By looking at Fig. 16 the descending dark curve shows the mass yield over the temperature, while the orange curve represents the derivative of the mass yield curve, allowing to detect the temperatures corresponding to variations in the behavior of the sample.
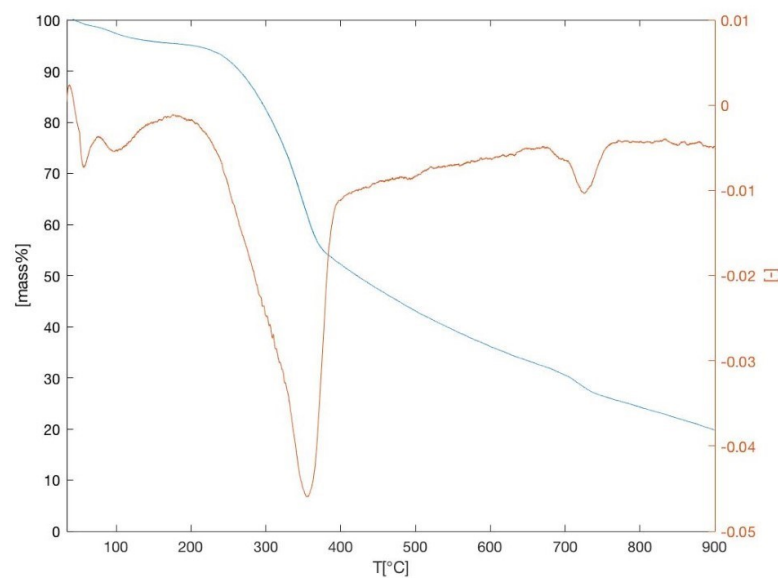
Figure 16 TG analysis of the bark sample

It is worth mentioning that possible differences (if compared with wood) can be detected just in the final part of the graph in the temperature range between 700 and 800 °C. The pick noticeable in that range could be related to the presence of low temperature melting ashes (which could be problematic inside the plant).

2.7.2 Over sieve residual material: Compost out of specification

Table 16 shows the results of the elemental analysis for the different fractions separated in the compost out of specification.

Table 16 Results of the characterization of the different macro-fractions analysed separately (from compost out of specification samples) expressed as average values

		Mix (Ligno-cellulosic material+ plastic)	Ligno-cellulosic material	Fine fraction	Plastic fraction
moisture	%wb	4.57 ± 0.14	4.00 ± 0.02	2.48 ± 0.193	0.01
ash	%db	18.8 ± 2.5	22.11 ± 1.3	44.7 ± 1	9.10 ± 1.1
C	%db	47.54 ± 0.39	45.36 ± 019	30.53 ± 2.33	71.26 ± 5.9
H	%db	6.43 ± 0.25	5.90 ± 0.07	3.77 ± 0.4	10.96 ± 1.27
O	%db	23.34 ± 0.59	25.29 ± 0.32	21.81 ± 2.69	7.86 ± 6.5
N	%db	1.05 ± 0.24	0.87 ± 0.07	1.57 ± 0.13	0.53 ± 0.24
S	%db	0.33 ± 0.08	0.47 ± 0.01	0.40 ± 0.04	0.29 ± 0.04
HHV_{dry}	MJ/kg	17.93 ± 1.13	16.42 ± 0.39	10.26 ± 0.78	32.91 ± 0.5
LHV_{dry}	MJ/kg	16.52 ± 1.13	15.14 ± 0.39	9.44 ± 0.78	30.51 ± 0.5
HHV_{Milne}	MJ/kg	21.48	19.83	11.97	37.66
LHV_{Milne}	MJ/kg	20.08	18.54	11.15	35.27

It can be noticed, in general, how all the different fractions in the material (apart from the plastic fraction) are characterized by high contents of ashes. Moreover, as explained in the previous paragraphs, the presence of inert material of big dimensions, increases even more the global ash content of the material.

In the next chapters, different configuration/mixes of the fractions listed in Table 16 (plus the inert fraction) will be proposed and evaluated in order to find the best configuration for the energy valorization.

2.7.3 Samples employed for the torrefaction pretreatment consideration: pellet and torrefied pellet

The results of the elemental characterization for the standard pellet and the pretreated one (torrefied) are reported in Table 17.

Table 17 Results of the characterization for standard pellet and torrefied pellet (torrefied at 250 and 270 °C) employed in the gasification tests samples expressed as average values

		Standard pellet	Torrefied perllet (Ttorrefaction 250°C)	Torrefied perllet (Ttorrefaction 270°C)
moisture	%wb	2.48	1.82	1.77
ash	%db	0.80	0.79	0.81
C	%db	49.90	50.59	52.87
H	%db	5.36	5.60	5.42
O	%db	43.95	42.88	40.73
N	%db	0.00	0.14	0.17

S	%db	0.00	0.00	0.01
HHV$_{dry}$	MJ/kg	18.76	19.23	20.00
LHV$_{dry}$	MJ/kg	17.59	18.00	18.82
HHV$_{Milne}$	MJ/kg	18.81	19.48	20.27
LHV$_{Milne}$	MJ/kg	17.64	18.26	19.09

Results shown in Table 17 highlights the results expected from the torrefaction pretreatment. In particular, an increase of the carbon content on dry base and a reduction of the oxygen content can be noticed starting from the tandard pellet to the torrefied ones. These results are translated in an higher LHV value for the pretreated samples.

Fig.17 shows the clear effect of energy density increase produced by torrefaction processes, explained in the introduction chapter.
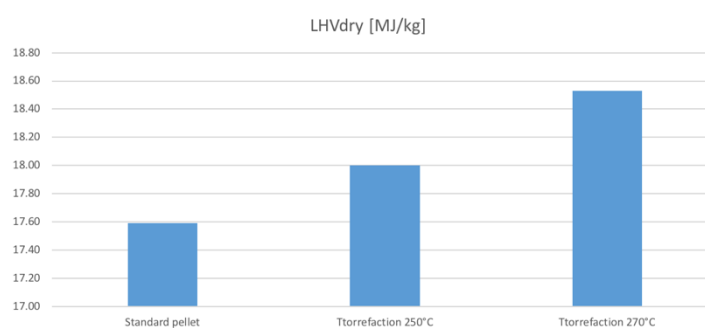
Figure 17 Trend of the LHV caused by torrefaction process

As mentioned in the introduction chapter, a mass loss caused by the more fragile structure of the pellet, have been registered. Data relative to this phenomenon are shown in Table 18.

Table 18 Mass loss (expressed in terms of percentage on the global mass of the sample) detected in the torrefied samples

	%$_{not\ recoverable\ fine\ fraction}$
Standard pellet	-
T$_{torrefaction}$ 250°C	10%
T$_{torrefaction}$ 270°C	6%

The mass loss detected could represent a problem from the management point of view of a gasification reactor, producing obstructions in the voids between material particles (pellets). In any case, the fine powder detected is not actually a loss from the global point of view of the process, but a recovery process of that material would require additional steps (which are probably not feasible from the economic point of view).

Chapter 3

Gasification

3.1 Gasification theory

Gasification process allows the conversion of a solid or liquid feedstock into a gaseous fuel which can be employed for energy purposes, as introduced in the first chapter.

Typical steps involved in a gasification process are [13]:
- Drying;
- Pyrolysis;
- Partial combustion of the released gases an char;
- Gasification of the products of the previous steps.

The drying phase takes place thanks to the heat coming from the oxidation zone downstream. It must be highlighted the fact that, in order to achieve satisfying heating values in the syngas, usually the employed systems are fed with feedstock characterized by moisture content in the range 10-20% [13].

Pyrolysis phase involves the thermal cracking of hydrocarbon molecules of the feedstock producing smaller gaseous molecules which can be condensable or not. Condensable part of this product brings to the formation of tars which could create problems in the plant management, thus the produced gas is treated for their reduction (further considerations concerning tars control will be explained in next pages). Fig.18 shows a generic scheme of a downdraft gasifier.
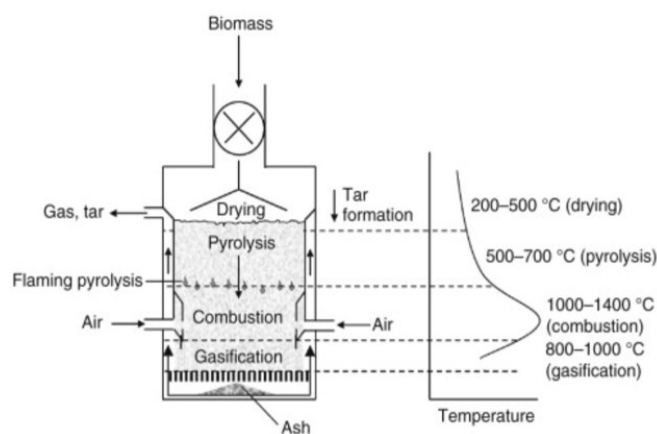
Figure 18 Generic scheme of a downdraft gasifier and its temperature profile [13]

Partial combustion of char is necessary to sustain most of the reaction of the process which are endothermic. Most important oxidation steps involves the reaction of carbon with the production of CO_2 and CO.

As will be explained in the next paragraphs concerning the gasifier employed in the laboratory, the control of the secondary air is crucial for the control of the

char conversion. The conversion of carbon into CO or CO_2 could be described using a partition coefficient, whose expression was proposed by Arthur (1951) [13]:

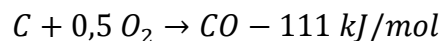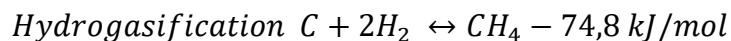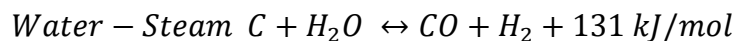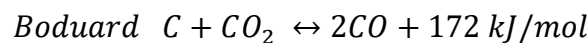$$\beta C + O_2 \rightarrow 2(\beta - 1)CO + (2 - \beta)CO_2 \quad (3.1)$$

Where β can be estimated according to Arthur as:

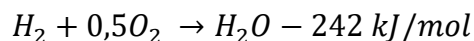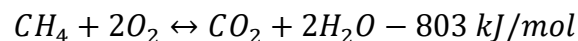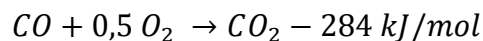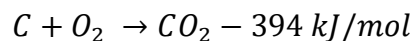$$\beta = \frac{[CO]}{[CO_2]} = 2400\, e^{-(\frac{6234}{T})} \quad (3.2)$$

T is the temperature of the char surface. Finally, gasification reactions follows pyrolysis, bringing to the final conversion pf the products of the previous steps into CO, H_2, CO_2 and H_2O. Between all the possible reactions, the ones involving char are the most important and listed below.
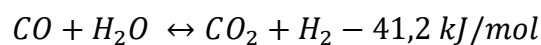The typical reactions involved during gasification process are [13]:
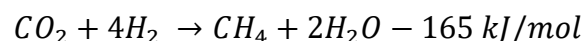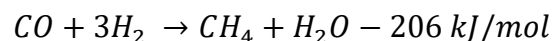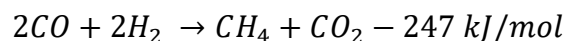
Carbon reactions

$$Boduard \quad C + CO_2 \leftrightarrow 2CO + 172\, kJ/mol$$

$$Water - Steam \quad C + H_2O \leftrightarrow CO + H_2 + 131\, kJ/mol$$

$$Hydrogasification \quad C + 2H_2 \leftrightarrow CH_4 - 74{,}8\, kJ/mol$$

$$C + 0{,}5\, O_2 \rightarrow CO - 111\, kJ/mol$$

Oxidation reactions

$$C + O_2 \rightarrow CO_2 - 394\, kJ/mol$$

$$CO + 0{,}5\, O_2 \rightarrow CO_2 - 284\, kJ/mol$$

$$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O - 803\, kJ/mol$$

$$H_2 + 0{,}5O_2 \rightarrow H_2O - 242\, kJ/mol$$

Shift reaction

$$CO + H_2O \leftrightarrow CO_2 + H_2 - 41{,}2\, kJ/mol$$

Methanation reactions

$$2CO + 2H_2 \rightarrow CH_4 + CO_2 - 247\, kJ/mol$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O - 206\, kJ/mol$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O - 165\, kJ/mol$$

Steam reforming reactions

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 + 206\, kJ/mol$$

$$CH_4 + 0{,}5\, O_2 \rightarrow CO + 2H_2 - 36\, kJ/mol$$
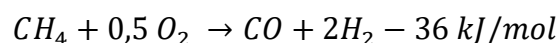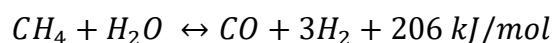
Possible gasifying mediums are air, pure oxygen or water steam. The choice of the medium has a strong influence on the final characteristics of the obtained syngas in terms of heating value (steam and pure oxygen gasification ensure much higher energy dense syngas), but from the technical and economic point of view, air gasification is much more easier to be achieved.

3.2 Gasification equipment

The plant adopted for the laboratory test is a small scale open top gasifier placed at the Free University of Bolzano (Fig.19) and developed at the Indian Institute of Science, Bangalore (India)

Figure 19 Picture of the open top gasifier in Free University of Bolzano and on the right, the main reactor

The system is characterized by a downdraft open top structure, which presents a cylindrical reactor (Fig.19, right), with the following geometrical main dimensions:
- Diameter: 120 mm;
- Height: 1000 mm.

The reactor has a double-stage air feeding, meaning that primary air is fed from the upper part of the gasifier (and controlled thanks to the presence of an inverter connected to the blower motor), while the secondary air flowrate can be controlled by means of the presence of nozzle placed at 670 mm from the reactor top (blue tube shown in Fig.19). This configuration allows to achieve an higher burn out of the char (which is placed in the bottom section of the reactor) [30]. The presence of a screw conveyor in the lowest section allows to control manually the char discharge.

Gasification reactors produce a syngas which contains tars and particles, thus the following components are adopted:

- **Cyclone** for the particle removement (Fig.20, left);
- Two water **scrubbers** for tars and particle removement**;**
- **Condenser** for water vapor removement;
- **Fabric filter** for particle removement (contained in the component shown in Fig 20,right).

Figure 20 On the left side, the cyclone separator during maintenance operations, on the right figure, the fibric filter container

The water used in the scrubbers is recirculated by means of a pump and passes through a dedicated tank (Fig. 21), which is periodically filled during the gasification tests also with ice with the aim to increase the effectiveness of the scrubbers (according to Henry's law, the solubility decreases with temperature).

Figure 21 Dedicated tank for the scrubbers water (containing water+ ice)

The equipment mentioned for tars and particles removement is of course adopted also at industrial level. Typical limits admitted by internal combustion engines and turbines are shown in Table 19.

Table 19 Limits of tars and particles concentrations for syngas utilization in ICE and turbines [12]

	Gas engine	Gas turbine
LHV [MJ/Nm^3]	> 2	> 5
Tar [mg/Nm^3]	< 100	< 5
Particle [mg/Nm^3]	< 50	< 30
Particle size [μm]	< 3	< 5
Ammonia [mg/Nm^3]	< 30–55	
H$_2$S [mg/Nm^3]	< 1,150	< 1
Alkalis [mg/Nm^3]	< 50	< 3
Halogens [mg/Nm^3]	< 100	< 2

A **torch** (shown in Fig.22, above) is directly connected to the producer gas line and in particular, if no ICE (internal combustion engines) are coupled with the plant, the entire flowrate (apart from the quantity sampled and sent to the gas chromatographer) is sent to the combustion in the torch.

The temperatures in different parts of the reactor and the system are measured by means of K-type thermocouples, connected with the acquisition system. The latter is managed by means of a LabView interface. Fig.22 shows a schematic representation of the plant employed for the gasification test in the LabView interface.
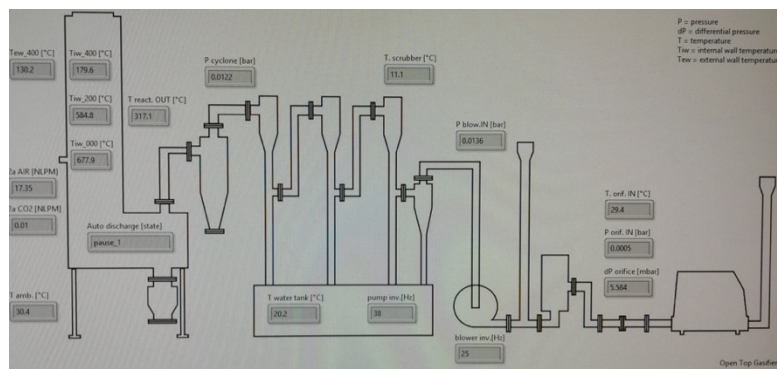
Figure 22 Torch employed for the direct combustion of the syngas (above) and scheme of the plant from the software LabView interface

The gas composition during the tests is performed by coupling the gasifier with a gas chromatographer (*3000 microGC, SRA Instruments*). Before entering into the gas chromatographer, it must be ensured the absence of any tar particle or steam, thus a column of **bubblers** (Fig.23) filled with propanol (for tars solubilization) and a filter containing **silica gel** to ensure the complete absence of water in the syngas.

Note that Fig.23 (right) shows the bubblers columns submerged in a ice tank needed to avoid the evaporation of the propanol.
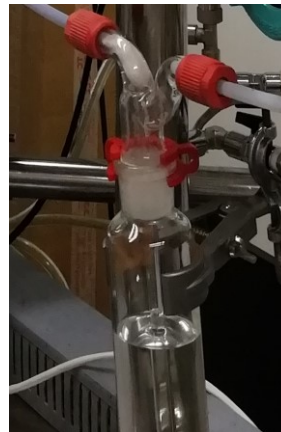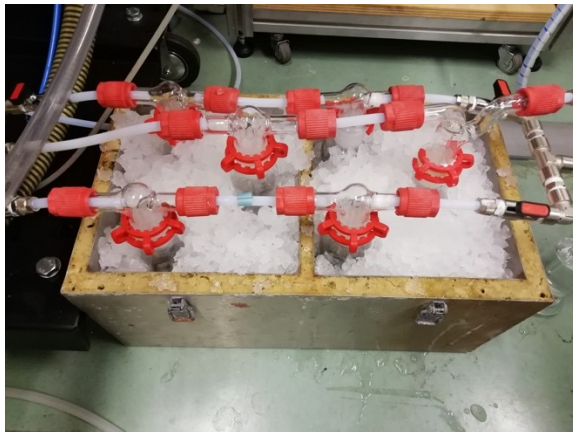

Figure 23 Column of bubblers filled with propanol (ice is used to avoid evaporation of the propanol)

3.3 Calculation procedure

Starting from data obtained from the measurements on the systems it is possible to compute the characteristic parameters of the process. The first step is the determination of the cycles of biomass charging. Fig. 24 shows schematically the reactor behavior.
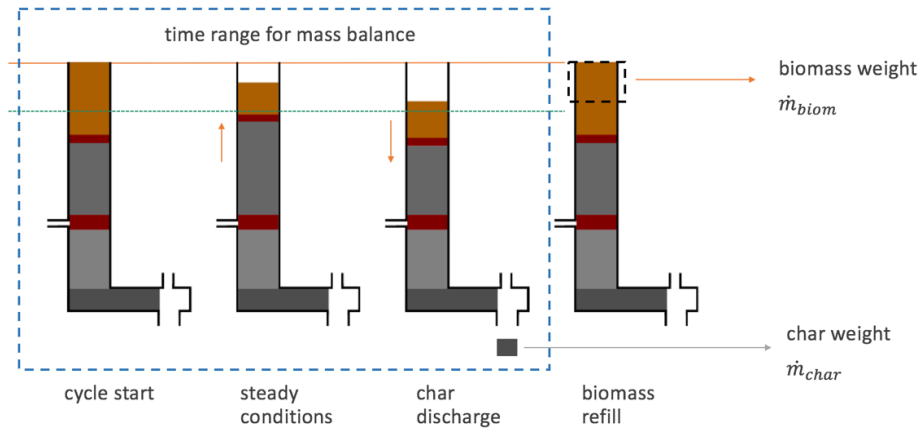

Figure 24 Schematic behaviour of the open top small scale gasifier [31]

Thus, the biomass flowrate can be computed according to Eq.3.3 (with the same relation, also the char flowrate can be computed):

$$\dot{m}_{biomass} = \frac{m_{biomass,input}}{t_{start} - t_{end}} \qquad (3.3)$$

where:

$m_{biomass,input}$ is the weight of the biomass sample charged at the end of the cycle in [g];

$t_{start} - t_{end}$ is the time interval between starting instant and ending instant of the cycle [h]

The following parameters are measured in the system in order to compute the syngas density (and consequently the volume flowrate of syngas) and the syngas composition from which its LHV is derived:

- Ambient temperature in the gasifier room t_{amb} [°C];
- Temperature at the orifice inlet $t_{g,orifice}$ [°C];
- Temperature at the reactor outlet $t_{g,out}$ [°C];
- Pressure difference between inlet and outlet section of the orifice ΔP [mbar];
- Syngas composition by means of the gas chromatographer.

Each of these values has been taken as the average computed in the time interval of interest for each cycle.

The syngas flowrate can be computed by means of the measurement of its temperature and the pressure difference ΔP at the orifice. The flowrate of produced gas (on dry base) is computed according to Eq. 3.4:

$$\dot{V}_{syngas} = A_0 \, C_{orifice} \, \sqrt{2 \, \Delta P / \rho} \qquad (3.4)$$

where the product $A_0 \, C_{orifice}$ has been estimated by means of a calibration with an anemometer gas flow meter and found to be equal to 1.28.
The density ρ of the syngas has been estimated starting from the composition on dry base given by the µGC (gas chromatographer), which detects the molar fraction of H_2, N_2, CO, CO_2, O_2, CH_4 and C_2H_6.
The average density of the syngas for each cycle can be computed as :

$$\rho = \frac{P}{\hat{R} \, T} \qquad (3.5)$$

where:
P is the pressure of the gas in [Pa];
T is the temperature of the gas equal to $t_{g,orifice}$ in [K]
$\hat{R}$ is the gas constant [J/kg K] computed as:

$$\hat{R} = \left(\frac{R}{M_m} \right) * 1000 \qquad (3.6)$$

With R= 8,31446 [J g^{-1} K^{-1}] and M_m is the molar mass of the syngas in [g mol^{-1}] computed as the weighted average of the single molar masses of each measured species, weighted on the molar fraction.

Finally, the mass flowrate of the syngas in [kg/s] can be computed as:

$$\dot{m}_{syngas} = \dot{V}_{syngas} \, \rho_{syngas} \frac{1}{3600} \qquad (3.7)$$

With the same approach used for the density, also the low heating value (LHV) can be computed as the weighted average of the LHV of each oxidable species:

$$LHV_{syngas} = \Sigma \, LHV_i \, y_i \qquad (3.8)$$

The total air mass flowrate involved in the process can be computed starting from the Nitrogen balance:

$$\dot{m}_{air}\,[N_{2,air}] = \dot{m}_{syngas}\,[N_{2,syngas}]\quad(3.9)$$

where:

$[N_{2,air}]$ is the mass fraction of nitrogen in the air (76,7%);

$[N_{2,syngas}]$ is the mass fraction of nitrogen in the syngas (from µGC).

A global mass balance can instead be done according to the Eq. 3.10:

$$\dot{m}_{biomass,as\,received} + \dot{m}_{air} = \dot{m}_{syngas} + \dot{m}_{H_2O+tars+particles,syngas} + \dot{m}_{char}\quad(3.10)$$

where $\dot{m}_{H_2O+tars+particles,syngas}$ is the water, tar and particle content of the syngas (that are not measured separately).

Considering now the characteristic parameters of the gasification process, we have:

Equivalence ratio

$$ER = O_{2,actual}/O_{2,stoichiometric}\quad(3.11)$$

Where the actual content of oxygen and the stoichiometric one are computed according to the equations 3.12 and 3.13 respectively:

$$O_{2,actual} = \dot{m}_{air}\,[O_{2,air}]\quad(3.12)$$

$$O_{2,stoichiometric} = \dot{m}_{biomass}\,(2{,}667\,C + 8\,H + S - O)\quad(3.13)$$

In which, C,H,N,S and O are the mass fractions of carbon, hydrogen, nitrogen, Sulphur and oxygen in the feedstock.

Cold Gas Efficiency

$$CGE = \frac{\dot{m}_{syngas}\,LHV_{syngas}}{\dot{m}_{biomass}\,LHV_{biomass}}\quad(3.14)$$

Which can also be expressed as the ratio of the outlet useful energy P_{out} to the input energy P_{in}.

Specific Producer Gas energy

$$SGE = \frac{\dot{m}_{syngas} \, LHV_{syngas}}{\dot{m}_{biomass}} \quad [\frac{kWh}{kg_{biomass}}] \quad (3.15)$$

Char yield

$$y_{char} = \frac{\dot{m}_{char}}{\dot{m}_{biomass}} \quad (3.16)$$

Of course, all these parameters can be considered to be an index of the efficiency of the reactor. For what regards the char yield, a small value is wanted since its presence at the end of the gasification represent a loss in terms of energy potential, and moreover it must be disposed, producing a cost.
A global char yield has been computed for each typology of gasified biomass (i.e. pellets and woodchips+bark) as the average of the single yields measured at each char discharge during all the tests with the same type of material and process conditions.

3.4 Performed gasification tests

Gasification tests have been performed with the aim of understanding the effect of bark content during a gasification process. The focus of this work is in fact to evaluate the possibility of implementation of biomass residues in a gasification plants, achieving in this way savings in terms of input biomass purchase. Moreover, the results of the gasification tests have been exploited for the calibration of a thermodynamic model used to simulate the gasification process of the compost out of specification (second residue evaluated).

The gasification tests have been performed with two different feedstock typology: woodchips and pellets. Pure woodchips have been used as reference material in order to have a comparison with the results in the case of different bark contents (pure woodchip, 30% bark content and 80% bark content) and moreover to understand the general behavior of the system.
As mentioned in previous chapters, the torrefaction process has been evaluated as possible pretreatment process with the aim of enhancing the characteristics of a residual biomass.

This evaluation has been performed by means of performing gasification tests starting from standard pellets and successively with torrefied pellets.

Torrefied pellets at two different torrefaction temperature have been employed during gasification tests (i.e at torrefaction temperatures equal to 250 and 270°C respectively).

During all the tests also the possibility of modulation of the air has been investigated, in order to find the best working conditions for the employed plant. For this purpose the secondary air (responsible for the conversion rate of the CO) has been set at four different values (i.e. 0, 17, 28 and 32 Nl m^{-1}).

3.4.1 Woodchip and bark tests

First gasification tests have than been performed with woodchips and bark. The first test has been done using pure woodchip (with a bark content of 8%) in order to obtain a reference to be compared with the tests performed with bark blends. The other two cases analyzed have been performed with a total bark content of 30% and 80%.

It must be said in advance that during the test performed with pure woodchips, the limits of the employed reactor have been found. From one side in fact, the lowest value of secondary air (i.e. 11 Nl/min) gave the worst results in terms of performances (CGE, char yield, LHV of the syngas and SGE), while the cycle performed at 26 Nl/min gave the best conditions in terms of CGE, SGE and LHV of the produced gas, but the fast char consumption detected suggested a dangerous condition in the combustion zone of the reactor.

The characteristics of the feedstocks obtained by means of the weighted average of bark and woodchips for the different tests are shown in Table 20.

Table 20 Characterization of the samples employed during the gasification tests (woodchips, woodchips with 30% and 80% bark content)

		Woodchips	Woodchips + Bark (30% blend)	Woodchips + Bark (80% blend)
moisture	%wt	10.90	10.70	7.87
ash	%wt	0.62	1.35	3.07
C	%wt	43.83	44.16	46.12
H	%wt	5.52	5.41	5.30
O	%wt	38.83	38.02	37.16
N	%wt	0.10	0.16	0.28
S	%wt	0.20	0.20	0.19
HHV	MJ/kg	17.44	17.51	18.13
LHV	MJ/kg	15.97	16.06	16.78

Fig.25 shows the samples used for the gasification tests in increasing order of bark content:

Figure 25 From left to right, samples of wood fraction without bark, 30% blend, 80% blend

The analysis of the measured parameters can start from the syngas composition in the different secondary air conditions, for each feedstock. Fig.26-28 show the syngas composition in terms of volumetric fraction for the pure woodchip, the 30% bark content and the 80% bark content respectively.
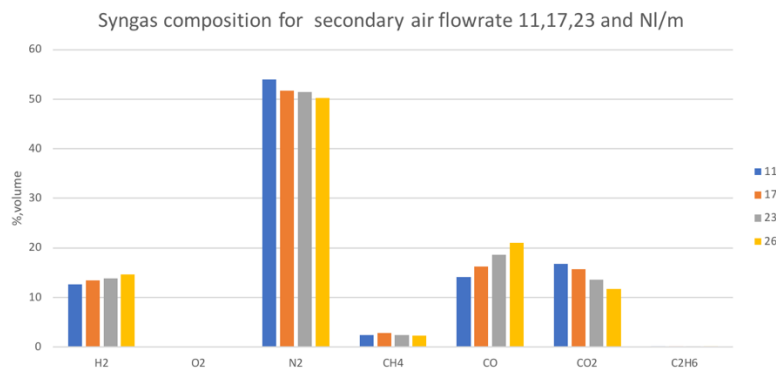
Pure woodchip

Figure 26 Syngas composition in different secondary air conditions for the pure woodchip
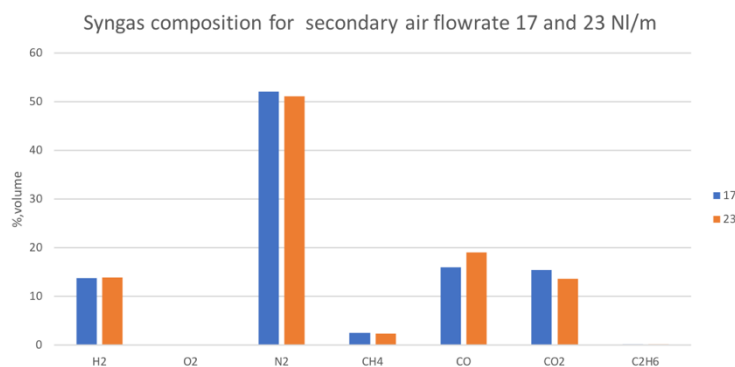
Woodchips and 30 % barks blend

Figure 27 Syngas composition in different secondary air conditions for the mix of woodchip and 30% bark
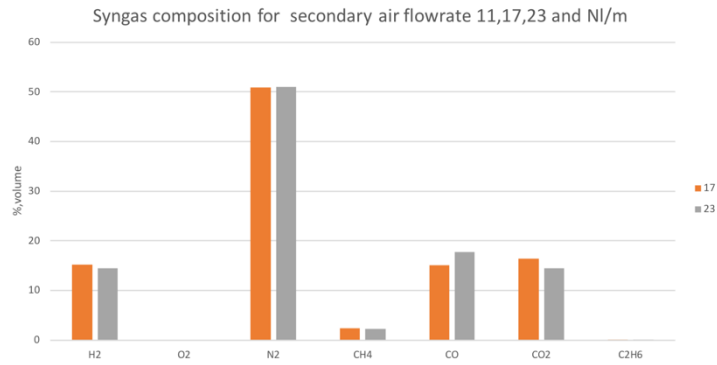
Woodchips and 80 % barks blend

Figure 28 Syngas composition in different secondary air conditions for the mix of woodchip and 80% bark

The general trend shown by each feedstock with the secondary air modulation is similar. A comparison of the syngas compositions between the three feedstocks in the same conditions is shown in Fig. 29-33 for the CO, H_2,CH_4,CO_2 and N_2 volume fractions respectively.

Figure 29 CO volume percentage for different secondary air and feedstocks

Figure 30 H_2 volume percentage for different secondary air and feedstocks

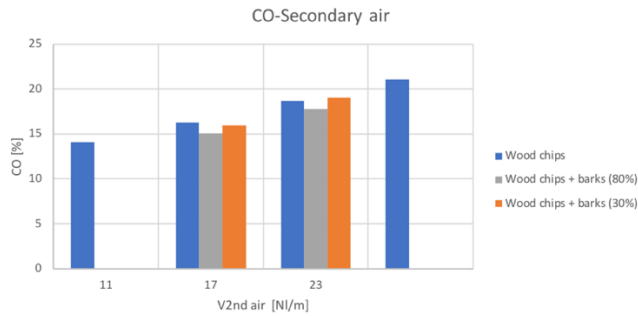*Figure 31 CH_4 volume percentage for different secondary air and feedstocks*
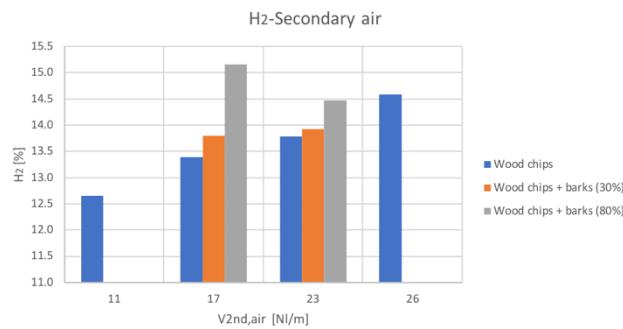
Figure 32 CO₂ volume percentage for different secondary air and feedstocks

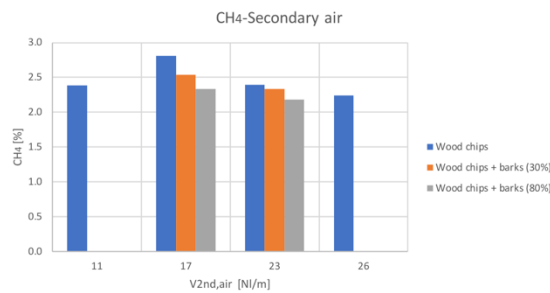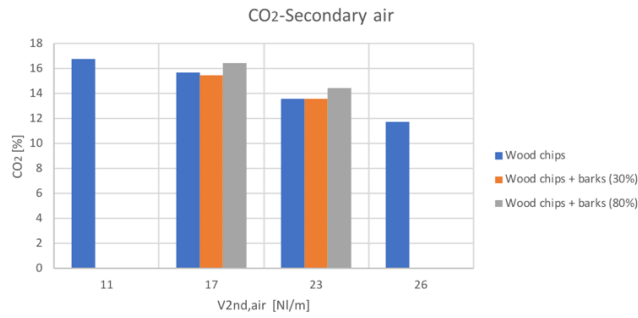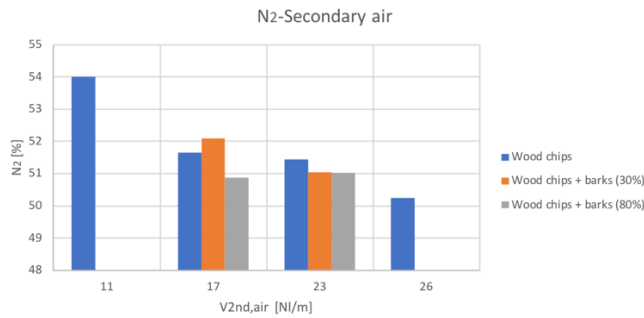*Figure 33 N₂ volume percentage for different secondary air and feedstocks*

The general trends are comparable with the only exception of the hydrogen content in the case of the 80% bark content blend. Anyway, it can be seen a general increase of hydrogen and carbon monoxide with secondary air increase, while a decreasing conversion with higher secondary air feeding can be instead noticed for CH_4 and CO_2.

The equivalence ratio behavior respect to the secondary air flowrate presents a general increasing trend. From equation 3.11 it is in fact easy to understand that an increase of the air flowrate in the char conversion zone produces an increase of the actual fed oxygen. This behavior is shown in Fig.34:
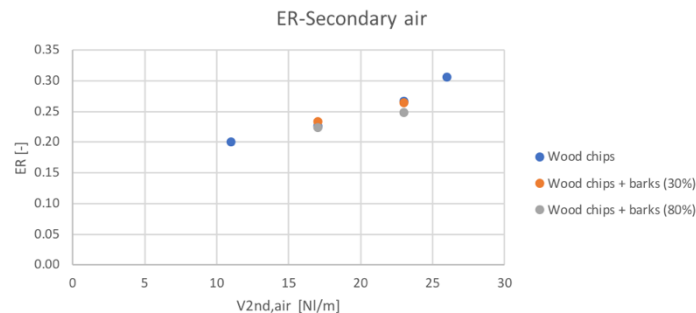

Figure 34 Variation of the equivalence ratio with the secondary air

The similar composition of the three feedstocks ensure similar ER values in each secondary air condition, with a slightly smaller value in the case of 80% bark

presence at 23 Nl/min. Anyway all the parameters will be shown for each feedstock against both secondary air and ER values.

As shown in Fig.35-36, the low heating value tends to increase together with the higher conversion into oxidable components in the producer gas.
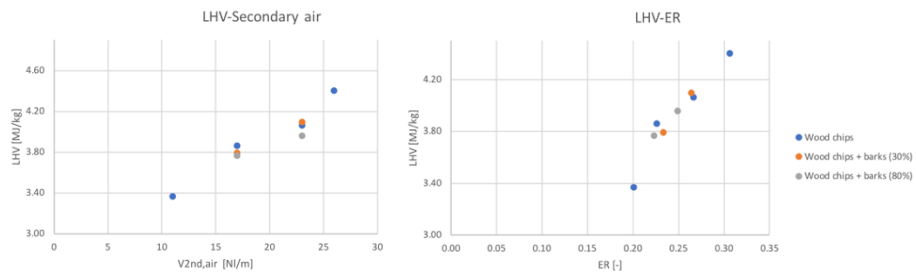

Figure 35 and 36 Low heating value for different feedstocks and Secondary air flowrate and ER

Considering the best detected condition of 23 Nl/min a slight increase of the LHV value can be noticed passing from the pure woodchip to the 30% content of bark (1%),while a reduction of the 2% have been obtained passing to the 80% bark content. The variability seems to be really negligible between tests.

As mentioned in the introduction paragraph of this chapter, the global performances of the gasification system can be evaluated on the base of the CGE, SGE and char yield. The results obtained during the gasification tests performed with woodchips and barks are reported in Fig.37-41.
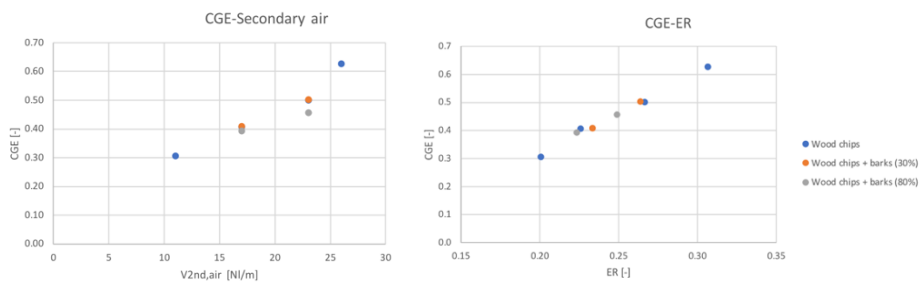
Figure 37 and 38 Cold gas efficiency value for different feedstocks and secondary air flowrate

The trends shown by the three different materials/blends are the same, and the only noticeable difference in terms of CGE can be seen in the case of the 80% content of bark for the 23 Nl/min condition, where a reduction of the 8% can be noticed. The increasing trend shown with the ER suggest a possible increase also for the bark with higher feeding of air.
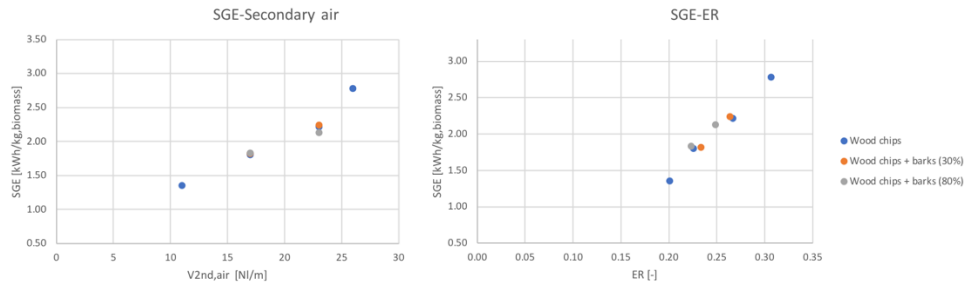
Figure 39 and 40 Specific producer gas energy value for different feedstocks and secondary air flowrate and ER

For what regards all the CGE, SGE and LHV parameters, a clear difference can be noticed in the case of the two "limit" conditions of the plant (i.e. 11 and 26 Nl/min secondary air flowrate).

Finally, the trend of the char yield for the three feedstocks is shown in Fig. 41.
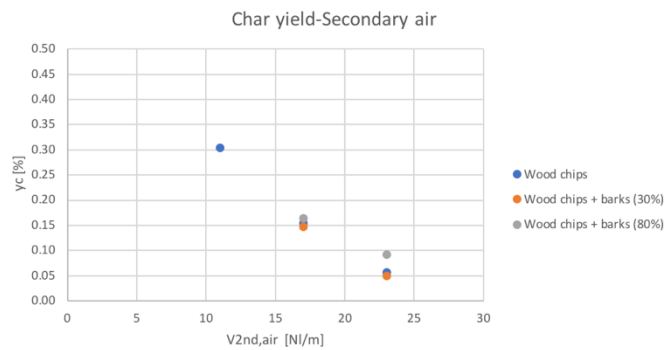
Figure 41 Char yield obtained from the gasification tests for each feedstock at different secondary air flowrates

The char yield obtained during the tests seems to be comparable for the three feedstocks in the same plant conditions. In all the cases, an increase of the air feeding in the char conversion zone is translated in a smaller char yield. Thus a global decreasing trend has been obtained. A noticeable difference occurs in the optimal case of 23 NL/min flowrate in which an increase of the 61% can be found passing from the pure woodchip to the 80% bark content.

In order to compute a power balance for the gasification system, the gas cooling power can be computed according to Eq. 3.17:

$$P_{gas\ coooling} = \dot{m}_{syngas}\, c_{p,syngas} \left(t_{g,out} - t_{g,orifice} \right) \quad (3.17)$$

where the $c_{p,syngas}$ is computed as the weighted average of the single values of each species. Moreover the energy not valorized by means of the char disposal can be than computed as the product of the char mass flowrate multiplied for an average value of LHV equal to 23 MJ/kg. Finally it is possible to access by difference, the thermodynamic losses through the reactor wall.

3.4.1.1 Mass and energy balances

The Sankey diagrams in Fig.42-44 show the mass and power balances computed respectively according to Eq.3.10 and as indicated in paragraph 3.4.1.
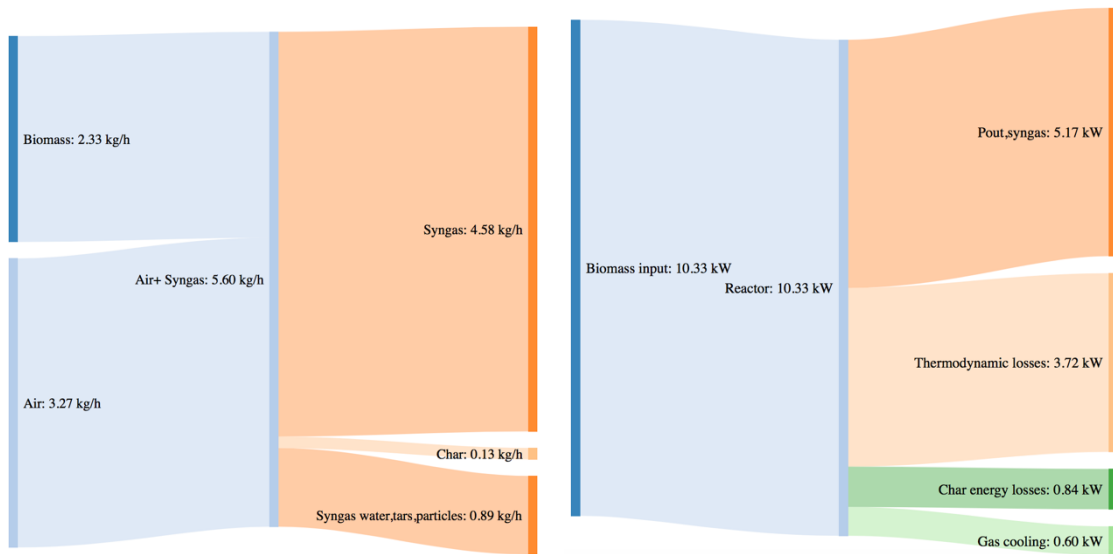
Figure 42 Mass and power balance for the pure woodchip gasification tests
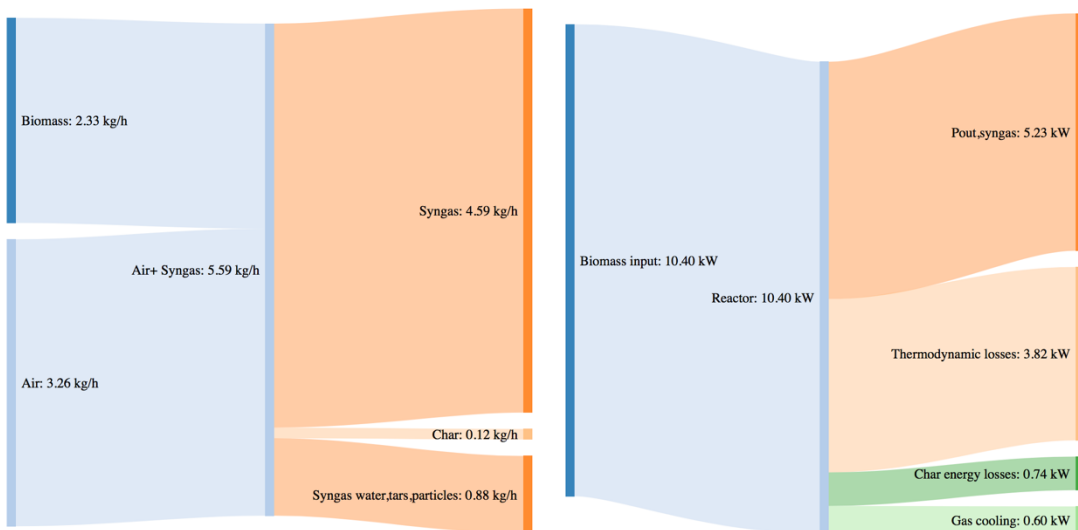
Figure 43 Mass and power balance for the mix of woodchip and bartk at 30% blend gasification tests
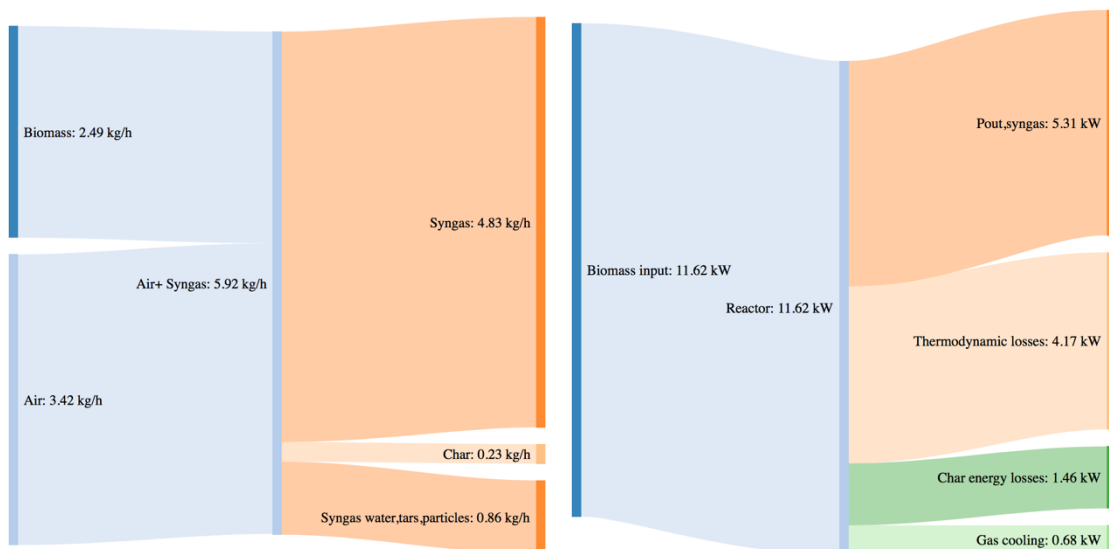
Figure 44 Mass and power balance for the mix of woodchip and bartk at 80% blend gasification tests

As shown by CGE in the previous paragraph, the three performances of the system are comparable in the same secondary air feeding conditions. The noticeable difference in terms of char yield in the case of the 80% bark content is translated in a higher power loos due to the not valorized char energy content. The biomass consumption in the best working conditions tends to increase with an higher content of bark, but the power output of the syngas is not characterized by a proportional increase. This phenomenon is translated in a smaller value of CGE.

Thermodynamic losses through the reactor wall are comparable for the three feedstocks utilization (corresponding to roughly 36% of the input power).

A resume of the performed tests with woodchips, 30% bark content blend and 80% content blend is shown in Table 21.

Table 21 Resuming table of the woodchip and bark gasification test

Wood chips

Time	Cycle duration [h]	Biomass input [g]	Char weight [g]	Biomass flowrate [g/h]	2nd air [Nl/m]	dP [mbar]	Char flowrate [g/h]	H2	O2	N2	CH4	CO	CO2	C2H6	psyngas [kg/m3]	msyngas [kg/h]	LHVsyngas [MJ/kg]	mair,tot [kg/h]	O2_actual [kg/s]	mbiomass [kg/s]	O2_stoich [kg/s]	ER	CGE	SGE [kwh/kg,biomass]	msyngas/mbiomass
13:58-14:04	0.10	326	99	3260	11	6.18	989	12.65	0.00	54.00	2.39	14.06	16.76	0.14	1.10	4.73	3.37	3.44	2.23E-04	9.06E-04	1.11E-03	0.20	0.31	1.36	1.45
14:04-14:45	0.68	1920	297	2810	17	6.28	434	13.39	0.00	51.65	2.81	16.29	15.70	0.17	1.08	4.73	3.86	3.34	2.16E-04	7.80E-04	9.57E-04	0.23	0.41	1.80	1.68
14:45-15:30	0.75	1747	99	2329	23	6.00	132	13.79	0.00	51.43	2.40	18.69	13.58	0.12	1.06	4.58	4.06	3.27	2.11E-04	6.47E-04	7.93E-04	0.27	0.50	2.22	1.97
15:30-17:20	1.83	3459	-	1887	26	5.37	-	14.58	0.00	50.25	2.24	21.06	11.78	0.09	1.04	4.28	4.41	3.04	1.97E-04	5.24E-04	6.42E-04	0.31	0.63	2.78	2.27

C	H	N	S	O						
0.438	0.055	0.001	0.002	0.388						
LHVbiomass	15.97	MJ/kg								

Char yield	mh2O,tars,particles		Pin	Pout,syngas	Ploss,gas cooling	Ploss,char	Pthermodynamic losses	
0.303	0.98		14.46	4.42	0.56	6.32	3.16	kW
0.155	0.99	kg/h	12.46	5.07	0.59	2.77	4.03	kW
0.057	0.89	kg/h	10.33	5.17	0.60	0.84	3.72	kW

Wood chips + barks (30%)

Time	Cycle duration [h]	Biomass input [g]	Char weight [g]	Biomass flowrate [g/h]	2nd air [Nl/m]	dP [mbar]	Char flowrate [g/h]	H2	O2	N2	CH4	CO	CO2	C2H6	psyngas [kg/m3]	msyngas [kg/h]	LHVsyngas [MJ/kg]	mair,tot [kg/h]	O2_actual [kg/s]	mbiomass [kg/s]	O2_stoich [kg/s]	ER	CGE	SGE [kwh/kg,biomass]	msyngas/mbiomass
15:37-16:23	0.77	2027	297	2644	17	5.92	387	13.80	0.00	52.08	2.54	15.96	15.47	0.15	1.07	4.57	3.79	3.27	2.12E-04	7.34E-04	9.06E-04	0.23	0.41	1.82	1.73
16:23-17:14	0.85	1981	99	2331	23	6.07	116	13.93	0.00	51.05	2.33	19.00	13.56	0.12	1.05	4.59	4.10	3.26	2.11E-04	6.47E-04	7.99E-04	0.26	0.50	2.24	1.97

C	H	N	S	O						
0.442	0.054	0.002	0.002	0.380						
LHVbiomass	16.06	MJ/kg								

Char yield	mh2O,tars,particles		Pin	Pout,syngas	Ploss,gas cooling	Ploss,char	Pthermodynamic losses	
0.146	0.955		11.79	4.82	0.58	2.47	3.93	kW
0.050	0.880	kg/h	10.40	5.23	0.60	0.74	3.82	kW

Wood chips + barks (80%)

Time	Cycle duration [h]	Biomass input [g]	Char weight [g]	Biomass flowrate [g/h]	2nd air [Nl/m]	dP [mbar]	Char flowrate [g/h]	H2	O2	N2	CH4	CO	CO2	C2H6	psyngas [kg/m3]	msyngas [kg/h]	LHVsyngas [MJ/kg]	mair,tot [kg/h]	O2_actual [kg/s]	mbiomass [kg/s]	O2_stoich [kg/s]	ER	CGE	SGE [kwh/kg,biomass]	msyngas/mbiomass
14:25-14:28	0.05	342	99	6840	11	6.55	1978	13.61	0.00	54.60	1.81	12.26	17.63	0.09	1.10	4.86	3.07	3.58	2.32E-04	1.90E-03	2.44E-03	0.09	0.13	0.61	0.71
14:28-15:20	0.87	2407	396	2777	17	6.75	456	15.16	0.00	50.88	2.34	15.05	16.44	0.12	1.06	4.87	3.77	3.42	2.22E-04	7.71E-04	9.92E-04	0.22	0.39	1.83	1.75
15:20-16:12	0.87	2160	198	2493	23	6.72	228	14.47	0.00	51.03	2.18	17.78	14.43	0.11	1.05	4.83	3.96	3.42	2.22E-04	6.93E-04	8.91E-04	0.25	0.46	2.13	1.94

C	H	N	S	O						
0.461	0.053	0.003	0.002	0.372						
LHVbiomass	16.78	MJ/kg								

Char yield	mh2O,tars,particles		Pin	Pout,syngas	Ploss,gas cooling	Ploss,char	Pthermodynamic losses	
0.289	3.58		31.88	4.15	0.57	12.64	14.52	kW
0.164	0.88	kg/h	12.94	5.09	0.63	2.92	4.30	kW
0.092	0.86	kg/h	11.62	5.31	0.68	1.46	4.17	kW

3.4.2 Pellet and pre-treated pellet

As mentioned in the introduction paragraph, the effect of the torrefaction pretreatment has been investigated by means of gasification of standard pellet (use as reference condition) proceding with torrefied pellets.
The characteristics of the feedstock used for the tests (LHV and the elemental characterization) of the feedstocks are reported in Chapter 2 for the dry material, while the moisture content during the test (as received) and the LHV relative to this condition are shown in Table 22.

Table 22 Characteristics of the pellet and torrefied pellet samples employed in the gasification tests

		Standard pellet	Torrefied perllet (Ttorrefaction 250°C)	Torrefied perllet (Ttorrefaction 270°C)
moisture	%wb	7.88	4.48	4.10
LHV	MJ/kg	16.01	17.09	17.67

An example of the samples used during the tests is shown in Fig.45:

Figure 45 Samples of a standard pellet and a torrefied pellet

The first noticeable effect of this secondary air modulation is the different conversion of CO and H_2. Fig.46-48 shows the different syngas composition for each feedstock for different secondary air feeding.

Standard pellet
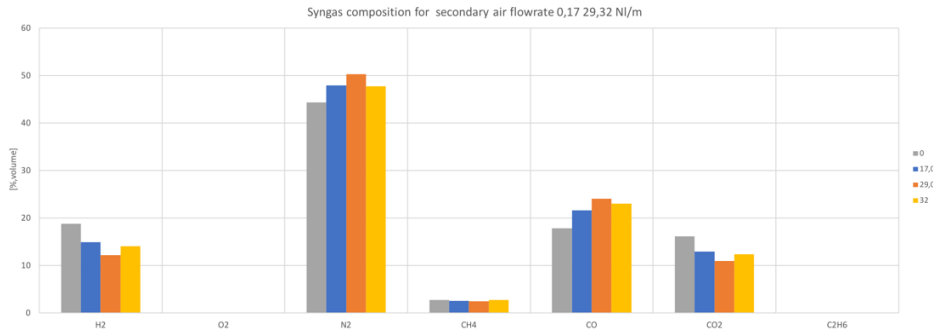
Figure 46 Syngas composition in different secondary air conditions for the standard pellet

Torrefied pellet (250°C)
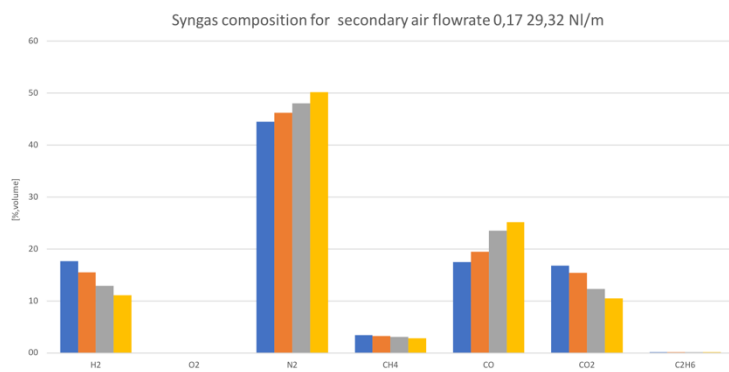
Figure 47 Syngas composition for different secondary air, of torrefied pellet (Ttorrefaction=250°C)

Torrefied pellet (270°C)
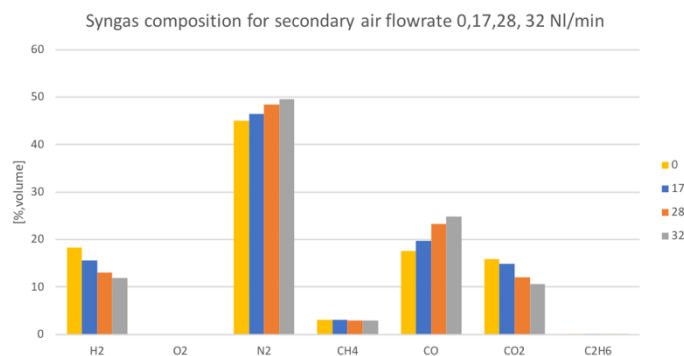
Figure 48 Syngas composition for different secondary air, of torrefied pellet (Ttorrefaction=270°C)

In all the cases, apart from the first one, similar trends for CO and H_2 can be noticed. In particular, by increasing the secondary air flowrate, the conversion into CO increases, while the H_2 decreases.

A first comparison between the three samples can be shown by means of the CO, H_2, CO_2, CH_4 and N_2 volume percentage as shown in Fig.49-52.
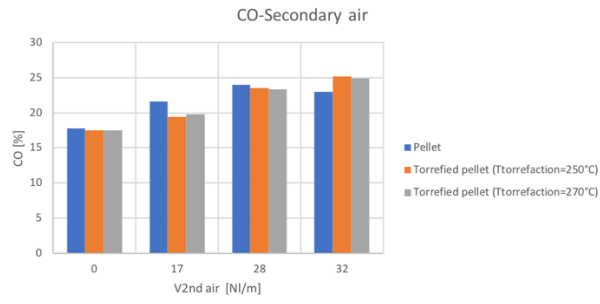
Figure 49 CO volume percentage for different secondary air and feedstocks
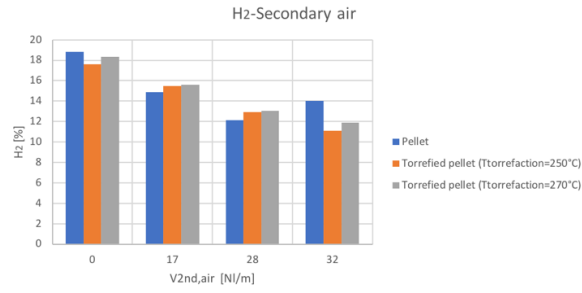
Figure 50 H_2 volume percentage for different secondary air and feedstocks
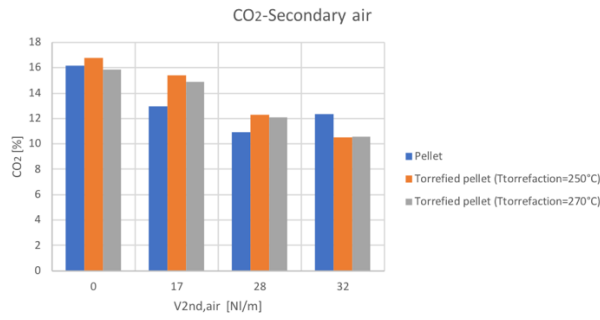
Figure 51 CO_2 volume percentage for different secondary air and feedstocks
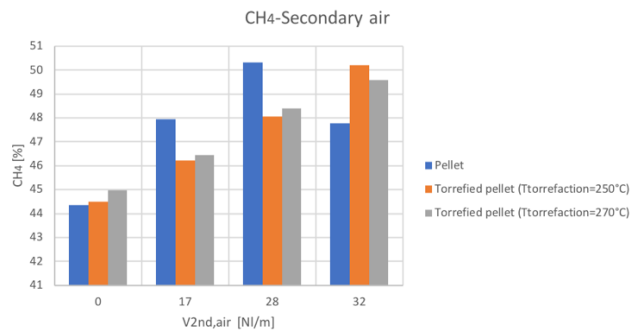
Figure 52 CH_4 volume percentage for different secondary air and feedstocks
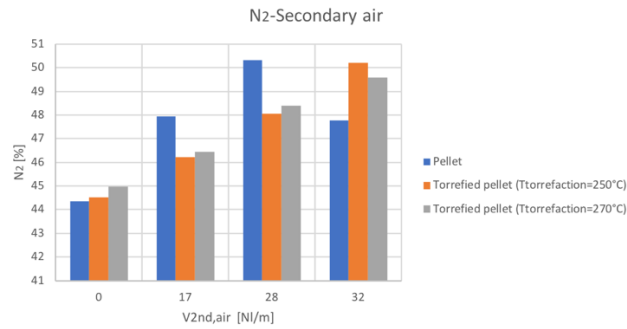
Figure 53 N$_2$ volume percentage for different secondary air and feedstocks

As mentioned, the general increase of CO content in the syngas can be noticed by increasing the secondary air feeding. Also the CH$_4$ tends to increase with secondary air feeding, not to mention the N$_2$ whose presence is directly connected to air flowrate. A decreasing trend is instead shown by the H$_2$ and CO$_2$.

For what regards the equivalence ratio behavior respect the secondary air flowrate, a general increasing trend can be noticed (Fig.54).
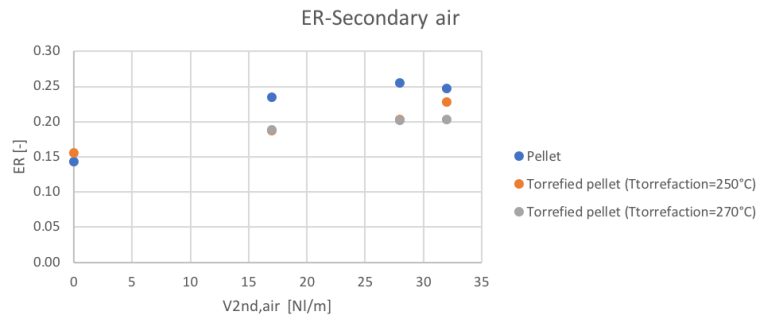
Figure 54 Variation of the equivalence ratio with the secondary air

The low heating value obtained in the different conditions can be seen in Fig.55 and Fig.56:
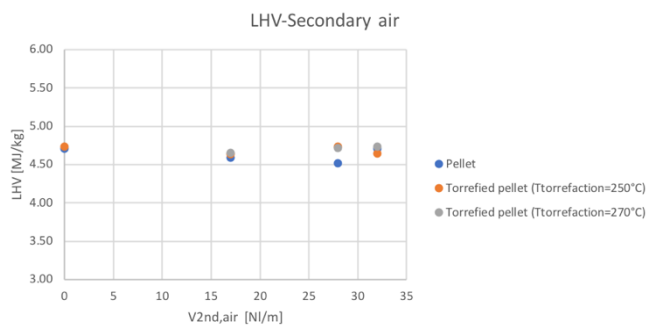
Figure 55 Low heating value for different feedstocks and Secondary air flowrate
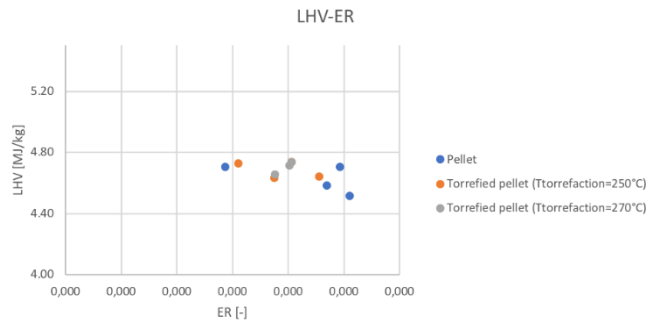
Figure 56 Low heating value for different feedstocks and ER

It can be noticed the fact that no significant differences in the LHV value have been obtained.

Considering now the parameters that give a representation of the efficiency of the reactor, Fig.57,58,59 and 60 show the trends of the cold gas efficiency and the specific producer gas energy with respect to the secondary air and ER value.
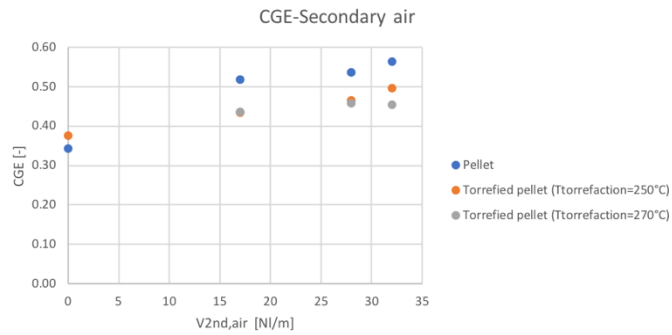
Figure 57 Cold gas efficiency value for different feedstocks and secondary air flowrate
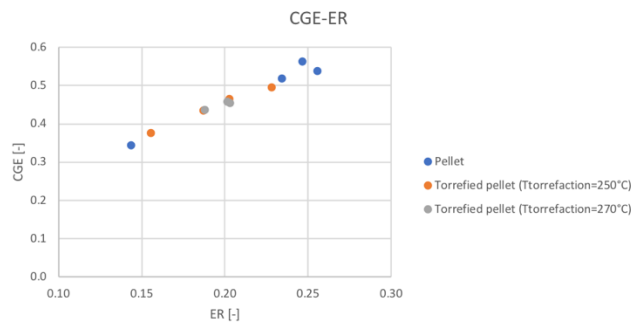
Figure 58 Cold gas efficiency value for different feedstocks and equivalence ratio
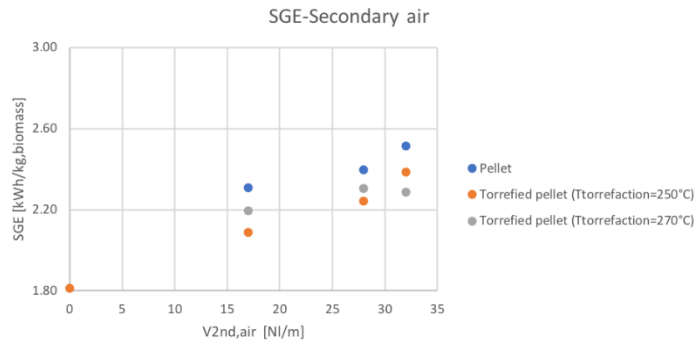
Figure 59 Specific producer gas energy for different feedstocks and secondary air flowrate
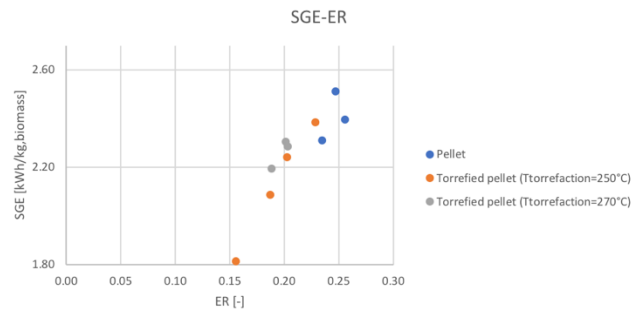
Figure 60 Specific producer gas energy for different feedstocks and equivalence ratio

It can be noticed how the torrefaction pretreatment seems to produce not the desired effect during the gasification process. In particular, in the same condition of secondary air feeding, the CGE and SGE are smaller for the pre-treated pellets. But looking at the behavior respect the ER (considering that also the ER is different in the same secondary air conditions for the different materials) the linear trends suggest the fact that going toward higher values of equivalence ratios, also in the case of the torrefied materials, higher values of cold gas efficiency and specific gas energy could be reached.
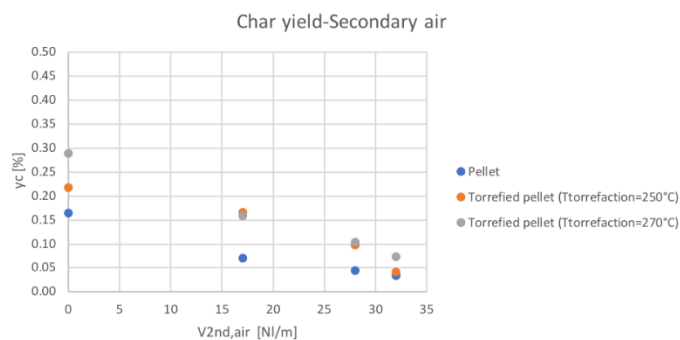
Figure 61 Char yield for different feedstocks and secondary air conditions

Even the char yield is higher in the case of the pre-treated material producing from the practical point of view a management problem of the plant, since char disposal represents a cost. By the way, a global decreasing trend (opposite to the CGE and SGE) has been found increasing the secondary air feeding and thus the char conversion.

3.4.2.1 Mass and energy balances

The mass and power balance for each feedstock are reported in Fig.62, 63 and 64 for the standard pellet, the torrefied pellet at 250°C and the torrefied pellet at 270°C respectively.
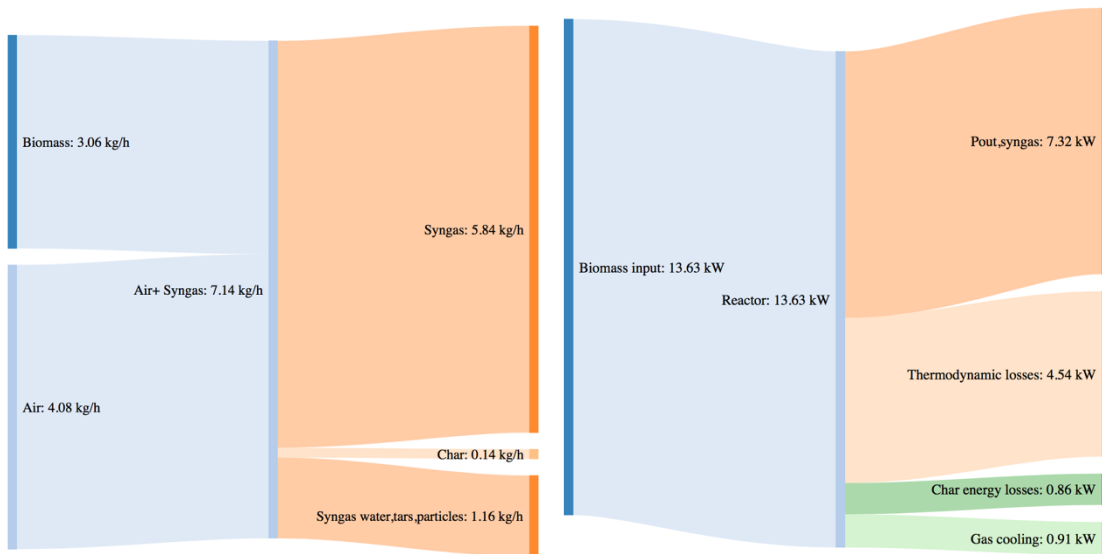

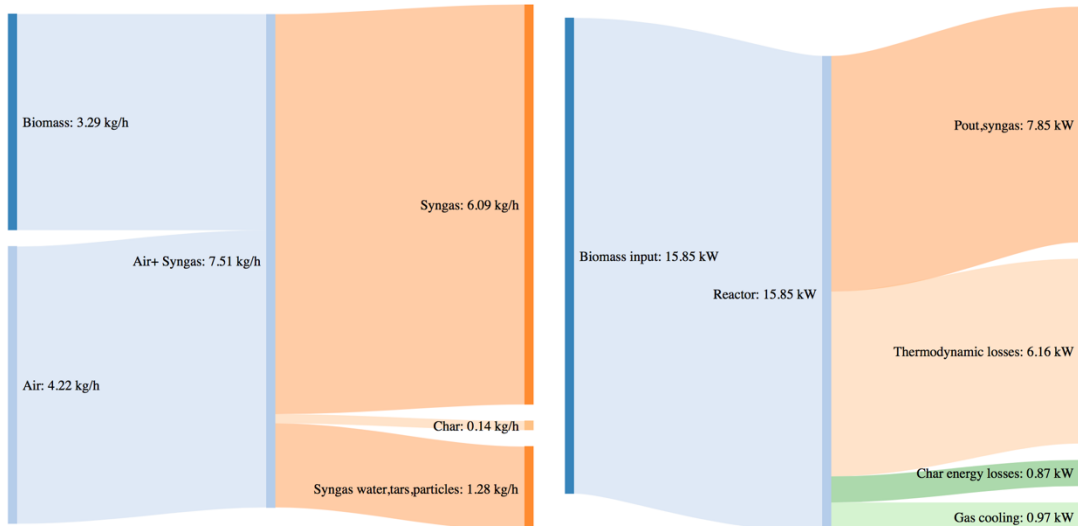*Figure 62 Mass and power balance for the standard pellet gasification tests*

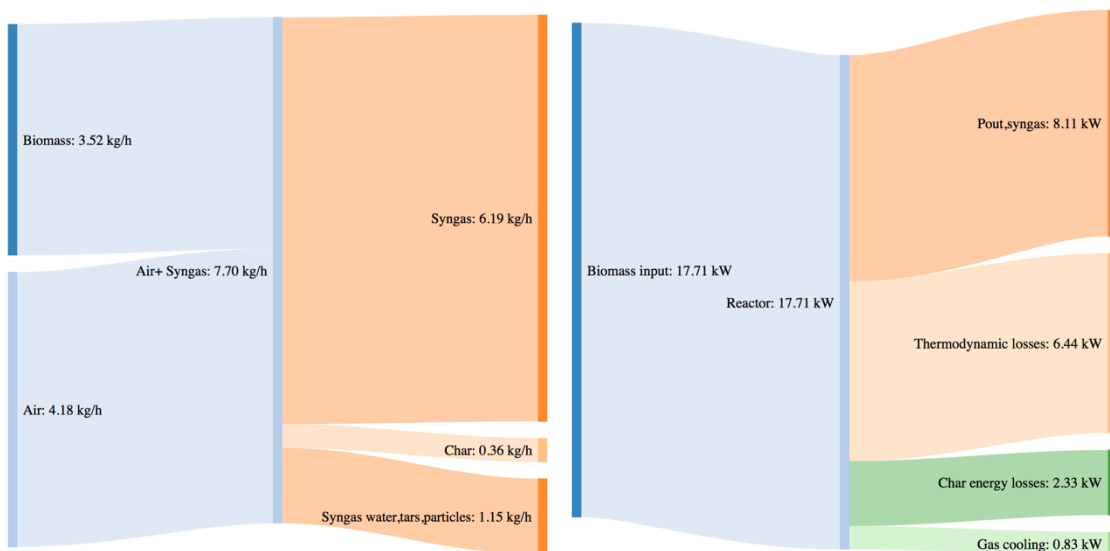*Figure 63 Mass and power balance for the 250°C torrefied pellet gasification tests*

Figure 64 Mass and power balance for the 270°C torrefied pellet gasification tests

The biomass consumption in the best working condition (corresponding to the highest value of CGE in each case), tends to increase passing from the standard pellet to the pretreated ones.

As expressed by the CGE behavior, that is smaller in the case of torrefied pellets in the same working conditions (i.e. same secondary air flowrate) the higher energy input provided by the torrefied pellets in terms of higher LHV value is not translated in a proportional output power of the syngas.

Moreover, the higher char yield leads, in the case of the pretreated samples, to an higher loss due to the not valorized energy content of the char.

The thermodynamic losses are in general comparable with the tests performed with woodchips and barks, but a slight variation can in this case be noticed passing from 33,3% (with respect to the input power) for the standard pellet, going to the 38,8% for the torrefied pellet at 250°C and 36,4% for the torrefied pellet at 270°C.

A resume of the performed tests with standard pellet and torrefied pellets is shown in Table 23.

Table 23 Resuming table of the balances and calculations performed with pellet tests

Main balance table

Test	Time	Cycle duration [h]	Biomass input [g]	Char weight [g]	Biomass flowrate [g/h]	2nd air [Nl/m]	dP [mbar]	Char flowrate [g/h]	H2	O2	N2	CH4	CO	CO2	C2H6	psyngas [kg/m3]	msyngas [kg/h]	LHVsyngas [MJ/kg]	mair,tot [kg/h]	O2,actual [kg/s]	mbiomass [kg/s]	O2,stoich [kg/s]	ER	CGE	SGE [kwh/kg,biomass]	msyngas/mbiomass
1-07 luglio (standard pellet)	13:59-15:54	1.92	6180	437	3224	17	10.05	228	14.88	0.00	47.94	2.55	21.58	12.95	0.11	1.03	5.84	4.59	3.95	2.56E-04	8.96E-04	1.09E-03	0.23	0.52	2.31	2.51
	15:54-16:59	1.08	3310	145	3056	29	9.95	135	12.15	0.00	50.31	2.48	24.02	10.91	0.12	1.04	5.84	4.52	4.08	2.64E-04	8.49E-04	1.03E-03	0.26	0.54	2.40	2.65
10-07 (standard pellet)	13:54-14:26	0.53	2656	437	4980	0	10.11	820	18.80	0.00	44.35	2.77	17.82	16.14	0.11	1.03	5.85	4.70	3.73	2.42E-04	1.38E-03	1.68E-03	0.14	0.34	1.53	1.63
	14:45-16:08	1.38	4258	145	3078	32	10.24	105	14.02	0.00	47.77	2.72	23.00	12.35	0.13	1.04	5.92	4.71	3.97	2.57E-04	8.55E-04	1.04E-03	0.25	0.56	2.51	2.66
2-07 (torrefied pellet 250°C)	13:22-13:40	0.30	1341	292	4470	0	11.09	972	17.63	0.00	44.51	3.43	17.47	16.79	0.16	1.04	6.17	4.73	3.90	2.52E-04	1.24E-03	1.62E-03	0.16	0.38	1.81	1.38
	13:40-14:07	0.45	1748	292	3884	17	11.49	648	15.50	0.00	46.22	3.24	19.45	15.42	0.17	1.05	6.31	4.63	4.08	2.64E-04	1.08E-03	1.41E-03	0.19	0.43	2.09	1.62
	14:07-14:56	0.82	2999	292	3672	28	11.29	357	12.92	0.00	48.06	3.06	23.51	12.29	0.16	1.05	6.26	4.74	4.18	2.71E-04	1.02E-03	1.33E-03	0.20	0.47	2.24	1.70
	14:56-17:05	2.15	7076	292	3291	32	10.69	136	11.12	0.00	50.20	2.84	25.17	10.53	0.15	1.05	6.09	4.64	4.22	2.73E-04	9.14E-04	1.20E-03	0.23	0.50	2.39	1.85
3-07 (torrefied pellet 270°C)	13:20-13:50	0.50	1829	292	3658	17	11.14	583	15.59	0.00	46.45	3.15	19.76	14.89	0.16	1.05	6.20	4.66	4.05	2.62E-04	1.02E-03	1.40E-03	0.19	0.44	2.19	1.70
	13:50-14:38	0.80	2813	292	3516	28	11.07	364	13.06	0.00	48.40	2.97	23.33	12.08	0.16	1.05	6.19	4.72	4.18	2.70E-04	9.77E-04	1.34E-03	0.20	0.46	2.31	1.76
	14:38-16:54	2.27	7869	583	3472	32	10.54	257	11.86	0.00	49.59	2.90	24.91	10.59	0.15	1.05	6.03	4.74	4.16	2.69E-04	9.64E-04	1.32E-03	0.20	0.45	2.29	1.74

Biomass composition (mass fractions) and LHV

Test	C	H	N	S	O	LHVbiomass [MJ/kg]
1-07 luglio (standard pellet)	0.460	0.049	0.000	0.000	0.405	16.06
10-07 (standard pellet)	0.460	0.049	0.000	0.000	0.405	16.06
2-07 (torrefied pellet 250°C)	0.483	0.053	0.001	0.000	0.410	17.33
3-07 (torrefied pellet 270°C)	0.506	0.052	0.002	0.000	0.392	18.13

Char yield and power balance

Test	Char yield	mh2O,tars,particles [kg/h]	Pin [kW]	Pout,syngas [kW]	Ploss,gas cooling [kW]	Ploss,char [kW]	Pthermodynamic losses [kW]
1-07 luglio (standard pellet)	0.071	1.10	14.38	7.45	0.86	1.46	4.62
	0.044	1.16	13.63	7.32	0.91	0.86	4.54
10-07 (standard pellet)	0.165	2.05	22.22	7.64	0.66	5.24	8.68
	0.034	1.02	13.73	7.73	0.89	0.67	4.44
2-07 (torrefied pellet 250°C)	0.217	1.23	21.52	8.11	0.55	6.21	6.65
	0.167	1.02	18.70	8.11	0.78	4.14	5.67
	0.097	1.24	17.68	8.23	0.92	2.28	6.24
	0.041	1.28	15.84	7.85	0.97	0.87	6.16
3-07 (torrefied pellet 270°C)	0.159	0.92	18.43	8.03	0.63	3.73	6.05
	0.104	1.14	17.71	8.11	0.83	2.33	6.44
	0.074	1.34	17.49	7.94	0.91	1.64	7.00

3.4.5 Problems encountered and possible solutions

- A periodic formation of "bridges" in the reactor has been noticed with intervals of few minutes. The formation of this structures in the biomass bed may be related to the local pyrolysis of the biomass and can produce important issues for the correct air flow in the reactor and the obstruction of the piping for syngas transportation [28].
  Possible solutions could involve the use of pneumatic hummers (employed at industrial level to avoid fouling of the boundle tubes in waste do energy plants);
- Maintenance operations performed on the system have shown that tars removement is not perfectly effective. The employment of diesel-fed scrubbers could increase the syngas cleaning effectiveness from this point of view.

3.5 Simulations by means of equilibrium approach application

Gasification tests with over-sieve fraction from anaerobic digestion plants (compost out of specification) have not been performed. Nonetheless, in order to have a preliminary assessment of the possible utilization of this material as feedstock in a gasification process, a thermodynamic equilibrium approach has been applied.

The approach has been applied by means of the use of the software Cantera (through the commercial software MATLAB®).

The model developed in Cantera, by means of the application of the equilibrium approach (briefly described in the section 3.5.1) has been calibrated on the base of the results obtained during the gasification tests performed with woodchips and pellets.

3.5.1 Equilibrium approach theory

As mentioned, the equilibrium approach is applied by means of the employment of the software Cantera. A brief description of the theory behind the equilibrium is presented in this section.

Considering a general reaction:

$$aA + bB \rightarrow cC + dD \qquad (3.18)$$
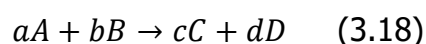
where a, b, c and d are the stoichiometric coefficients, two rate of reactions can be considered (r_1 and r_2). In any case, the rate of the reaction r_1 depends on the concentration of the reactants ($C_A^a \ and \ C_B^b$) by means of a relation like the (3.19) [13]:

$$r_1 = k_{foreward} \ C_A^a \ C_B^b \quad (3.19)$$

By considering the opposite direction for the reaction, we can consider a second rate r_2 which will depend on the concentration of C and D:

$$r_2 = k_{backward} \ C_C^c \ C_D^d \quad (3.20)$$

Naturally, at the beginning of the reaction, the concentration of A and B is high, thus $r_1 > r_2$ since the product concentration is still low. We can thus say that in these conditions, the reaction is not at equilibrium.
Going on with the reaction (and the production of C and D) the condition of $r_1 = r_2$ will be reached. In this conditions (equilibrium):
- Concentration of reactants and products is constant;
- $r_1 = r_2$;
- The Gibbs free energy of the system is at the minimum;

Under equilibrium conditions we can write:
$$k_{foreward} \ C_A^a \ C_B^b = k_{backward} \ C_C^c \ C_D^d \quad (3.21)$$

By means of the Arrhenius formula, the dependency of the constant k on the temperature T can be expressed:

$$k = A_0 \ \exp(-\frac{E}{RT}) \quad (3.22)$$

Where A_0 is a pre exponential constant, E is the activation energy for the reaction and R is the universal gas constant.

At this point, the equilibrium constant, given by the ratio of the foreword and backward constants can be writes an:

$$K_e = \frac{k_{foreward}}{k_{backward}} = \frac{C_C^c \ C_D^d}{C_A^a \ C_B^b} \quad (3.23)$$

The Gibbs free energy can be expressed as:

$$\Delta G = \Delta H - T \ \Delta S \quad (3.24)$$

Thus the variation of the Gibbs free energy can be computed as the enthalpy difference minus the product of the entropy difference multiplied for the temperature.

By using the Gibbs free energy (which can be computed for each of the species in a gas mixture) it is possible to compute the equilibrium constant K_e for a given temperature:

$$K_e = \exp(-\frac{\Delta G}{RT}) \quad (3.25)$$

The theory shown above is applied by means of the use of the software Cantera. The simulation of a gasification can be performed by means of the creation of a mixture of air in a quantity around 30% of the stoichiometric air and the biomass. The software finds the equilibrium of the mixture at the chosen temperature (750°C). The chosen temperature have been set according to the similarity of the obtained syngas compositions with respect to the experimental results (obtained with woodchip and pellet). As mentioned, the results of the equilibrium have been calibrated by means of the application of correction coefficients. The coefficients have been computed as the ratio between the molar fraction of each specie (H_2, N_2, CO, CO_2, O_2, CH_4 and C_2H_6) obtained from the experimental tests and the one obtained from the simulation with the software.

3.5.2 Simulation cases

In this section, the syngas composition obtained by means of the application of the procedure described in the section 3.5.1 is presented for the over sieve material.

Starting from the analysis of the different fractions of the over-sieve material (compost out of specification) shown in Table 16, different cases have been evaluated. In particular, the possibility of the separation of some of the fractions starting from raw material have been considered. The aim of the separation could be the possibility to achieve a better quality in terms of higher LHV and smaller content of ashes (as explained in the chapter relative to the characterization of the materials, some of the fractions present in the compost out of specification exhibit an high value of ash content, some are instead completely inert).

The characteristics of each configuration have been obtained starting from the initial weight fraction of each single material. The weight fractions have been re-computed for each specific case according to the separation of one or more material fraction.

The cases, evaluated starting from the separation of different fractions are the following ones:

- **Case 1: simulation of the gasification of the material as it is (compost out of specification)**

The first analyzed case for the energy valorization of the compost out of specification has been the one of the material as it is (composed by a ligno-cellulosic fraction, an inert fraction, a plastic fraction and a fine fraction).
The composition of the material as it is, is reported in Table 24.

Table 24 Elemental characterization of the compost out of specification as it is

		Material as it is
moisture	%wb	13.73
ash	%wt	37.27
C	%wt	28.54
H	%wt	3.83
O	%wt	15.71
N	%wt	0.71
S	%wt	0.21
LHV	MJ/kg	9.48

The results of the gasification simulation obtained starting from the composition shown in Table 24 by means of the application of the procedure described in the section 3.5.1 are shown in Table 25.

Table 25 Syngas composition obtained from the equilibrium simulation for the compost out of specification as it is

H_2	O_2	N_2	CH_4	CO	CO_2	C_2H_6
14.67	0.00	52.64	2.97	17.29	11.92	0.18

The LHV of the syngas obtained as the weighted average (weighting on the mass fractions) of each oxidable specie is equal to 4.31 MJ/kg.

- **Case 2: separation of the plastic and the fine fractions**

In this case it has been considered the possibility of separation of both the plastic fraction and the fine fractions. The composition of the material obtained from the separation of those fractions is shown in Table 26:

Table 26 Elemental characterization of the compost out of specification without fine and plastic fraction

		Ligno cell with inerts
moisture	%wt	12.80
ash	%wt	40.32
C	%wt	27.30
H	%wt	3.55
O	%wt	15.22
N	%wt	0.52
S	%wt	0.28
LHV	MJ/kg	8.63

The composition of the syngas obtained from the gasification simulation starting from the elemental characterization in Table 26 is shown in Table 27.

Table 27 Syngas composition obtained from the equilibrium simulation for the compost out of specification without fine and plastic fraction

H_2	O_2	N_2	CH_4	CO	CO_2	C_2H_6
14.43	0	52.62	2.98	17.62	12.00	0.18

The value of the LHV, computed according to the same procedure proposed for case 1, is in the case 2 equal to 4.31 MJ/kg.

- **Case 3: separation of the plastic fraction**

It must be highlighted the fact that the separation of the plastic fraction could just have the aim of obtaining a material admitted for the production of RDF "End of Waste" (CSS-combustibile) minimizing the possibility of presence of Cl (chlorine), whose presence must be strongly limited since it is precursor of PCDD/F. The composition of the material obtained from the separation of the plastic fraction is shown in Table 28.

Table 28 Elemental characterization of the compost out of specification without plastic fraction

		Ligno cell with inert and fine
moisture	%wt	13.40
ash	%wt	39.90
C	%wt	27.04
H	%wt	3.50
O	%wt	15.26
N	%wt	0.61
S	%wt	0.29
LHV	MJ/kg	8.48

As expected, a reduction of the LHV value can be noticed in Table 28 in comparison with the case 1 (material as it is).

Table 29 shows the composition of the syngas obtained from the gasification simulation for the material considered in Case 3.

Table 29 Syngas composition obtained from the equilibrium simulation for the compost out of specification without plastic fraction

H_2	O_2	N_2	CH_4	CO	CO_2	C_2H_6
14.55	0.00	52.40	2.85	17.36	12.29	0.16

The obtained LHV is in Case 3 equal to 4.3 MJ/kg.

- **Case 4: Material as it is without inert**

The material in this case is supposed to be obtained with just the separation, by means of a ballistic separator, of the heaviest inert. The aim of this procedure is to avoid the presence of an inert material during a gasification process (whose presence is responsible for a reduction of the LHV of the material). The separation of the inert fraction have been evaluated also from economic point of view in Chapter 4. The composition of the material obtained from the separation of the inert fraction is shown in Table 30.

Table 30 Elemental characterization of the compost out of specification without inert fraction

	Material without inert	
moisture	%wt	17.69
ash	%wt	18.53
C	%wt	37.14
H	%wt	4.98
O	%wt	20.45
N	%wt	0.92
S	%wt	0.28
LHV	MJ/kg	12.34

In Table 30, it can be noticed how an evident increase of the material (after the separation) have been obtained.

Table 31 shows the composition of the syngas obtained from the gasification simulation for the material considered in Case 4.

Table 31 Syngas composition obtained from the equilibrium simulation for the compost out of specification without inert fraction

H₂	O₂	N₂	CH₄	CO	CO₂	C₂H₆
14.20	0.00	53.09	3.23	18.09	11.42	0.22

The obtained LHV for the syngas composition obtained in Case4 is equal to 4.42 MJ/kg.

- **Case 5: Separation of the plastic and inert fraction**

By means of the combined effect of a ballistic separator and an aeraulic separator, the plastic fraction and the heaviest inert should be taken away. The aim of the separation of the plastic fraction s explained in the Case 3. The same stands for the separation of the inert fraction as in Case 4.
The composition of the material obtained from the separation of the plastic and inert fractions is shown in Table 32.

Table 32 Elemental characterization of the compost out of specification without inert and plastic fraction

		Ligno cellulosic + fine fraction
moisture	%wt	18.55
ash	%wt	20.75
C	%wt	35.15
H	%wt	4.55
O	%wt	19.84
N	%wt	0.79
S	%wt	0.37
LHV	MJ/kg	11.18

Table 33 shows the composition of the syngas obtained from the gasification simulation for the material considered in Case 5.

Table 33 Syngas composition obtained from the equilibrium simulation for the compost out of specification without inert and plastic fraction

H₂	O₂	N₂	CH₄	CO	CO₂	C₂H₆
14.20	0.00	52.79	3.06	17.99	11.84	0.20

The obtained value of LHV of the syngas obtained in Case 5 is equal to 4.34 MJ/kg.

The best conditions in terms of ash content and heating value seems to be obtained in Case 4 and 5, thus the ones created by separating the inert fraction of bigger dimensions.

Of course this separation of some fraction in the material needs to be evaluated from the economic point of view.

It is crucial to highlight the fact that the analysis proposed in sections 3.5.1 and 3.5.2 are purely theoretical. The real utilization of this material (compost out of specification) in a gasification plant should be evaluated on the base of experimental tests in order to draw more reliable conclusions from.

In particular, the high ash content often represents a plant management problem in existing plants. This aspect could be investigated also by means of deeper analysis performed on the ashes present in the material. Moreover, the heterogeneous nature of the material, coupled with the presence of plastics could lead to the necessity of further gas cleaning systems (i.e. Scrubbers for SO_x treatment, fabric filters for the predictable high particle filtration etc).

Chapter 4

4.1 Economic analysis

A technical and economic analysis is proposed in this chapter, with the aim of an evaluation of the feasibility of the energy valorisation of the residues under investigation.

The calculation procedure has been performed by means of using a tool developed by the IDM-Alto Adige (Innovation Development Marketing) for the project "Wood up" concerning the possibility of the char valorisation downstream of the gasification plants already existing in South Tyrol [32].

The tool implements all the benchmark data collected in the already existing plants in the region, thus the economic analysis have been performed considering the possibility of exploiting an existing configuration. Three technologies, using woodchip as input fuel, have been considered.

4.2 Calculation procedure adopted for the economic evaluation

A common methodology has been applied in the case of all the residues in order to have an estimation of the input parameter needed by the employed tool (i.e. $kg_{biomass}/kWh_{el}$).

As first step, the actual average biomass flowrate in [kg/s] has been computed from the benchmark data of annual consumption of biomass ($Total\ yearly\ biomass\ [t]$) and yearly working hours h_{year}:

$$\dot{m}_{biomass,actual} = \frac{Total\ yearly\ biomass}{h_{year}} \frac{1000}{3600} \left[\frac{kg}{s}\right] \quad (4.1)$$

Imposing a cold gas efficiency CGE_{actual} for a medium size plant equal to 0.8 and considering a low heating value of the woodchip LHV_{actual} of the actual plant equal to 16 MJ/kg, the input power for the benchmark case and the electric efficiency can be computed:

$$P_{in,biomass,actual} = \dot{m}_{biomass,actual}\ LHV_{actual}\ [kW] \quad (4.2)$$

$$\eta_{el} = \frac{P_{el}}{P_{in,biomass,actual}\ CGE_{actual}} \quad (4.3)$$

The need syngas mass flowrate can be computed, assuming an heating value equal to 4.5 MJ/kg, as:

$$\dot{m}_{syngas} = \frac{P_{el}}{LHV_{syngas}\ 1000} \left[\frac{kg}{s}\right] \quad (4.4)$$

In order to keep the same plant output and considering (from the gasification tests performed with a biomass residue) a reduction of the CGE of 8% respect the benchmark case, the residue (mix of bark and woodchip and sieving material from digestor) flowrate to be fed to the plant is:

$$\dot{m}_{residue} = \frac{\dot{m}_{syngas} \, LHV_{syngas}}{CGE_{new} \, LHV_{residue}} \left[\frac{kg}{s}\right] \quad (4.5)$$

Thus the annual residue request is:

$$m_{year,residue} = \dot{m}_{residue} \frac{h_{year}}{1000} \, 3600 \; [t/year] \quad (4.6)$$

And finally the input parameter expressing the needed feedstock biomass to feed the plant per unit of electric kWh is:

$$\frac{kg}{kWh} = \frac{m_{year,residue}}{En,el,actual} \quad (4.7)$$

Where $En, el, actual$ is the annual electric energy produced by the plant.

Having this parameters, the economic analysis can be performed with the aim of the calculation is to obtain the net cash flow, composed by the following voices:

Annual incomes
- Incetivated electric energy;
- Electric energy sold without incentives;
- Thermal energy sold.

Investment: total cost of the plant, computed starting from the specific cost of the chosen technology and accounting for the number of modules used plus the cost of added technologies (dryers and ballistic separator for the case study of the compost out of specification).

Annual operational costs
- Personnel cost: it is computed starting from the benchmark data obtained from plant interviews and expressed in terms of €/kWh$_{el}$ produced;
- Insurance: from benchmark data and expressed in terms of €/year;
- GSE (gestore servizi elettrici) administration procedures: from benchmark data and expressed in terms of €/year;
- Maintenance: expressed as specific cost per unit of produced electric energy €/kWh$_{el}$;
- Fuel cost: expressed as €/t;

- Mortgage cost: accounting for the fact that each instalment is composed by a capital component and an interest one. Interests are computed on the base of a constant rate, multiplied in each period for the remaining mortgage amount to be payed.

It must also be highlighted the fact that each year, the costs sustained by the plant and the price of the sold energy (earnings) are actualized by means of the consideration of an inflation rate as:

$$Cost_{year,n} = Actual\ value * \left(1 + i_{inflfaction}\right)^n$$

Where i_{year} is the annual inflation rate and n the year (thus accounting for a compound interest).

The following data have been taken constant for all the considered cases:
- Percentage of own capital (equity) 50%
- Bank rate 3.5%
- Mortgage duration 10 years;
- Inflation rate 1.5%
- Heat power sale price 80 €/MWh (and 40 % of the produced heat valorisation);
- Electric energy sale price 56 €/MWh (average weighted value in the three national hour slots);
- Duration of the investment 20 years.

For the production of ash/char after the gasification process, the char yield declared in the benchmark dates has been considered as starting value. The amount of ashes has than been added to that value. Thus the annual char production has been estimated as the sum of the ash content of the mixture and the part given by the char yield percentage considered.
In the case of the bark utilization instead, the char yield declared by the plant has been increased of the 60% according to the gasification results obtained in the laboratory and accounting for the fact that no modification in the plant would be made inserting barks.

The analyzed cases are:
- Introduction of barks in an existing plant switched on in 2012, after the end of incentives (15 years);
- Gasification of bark and woodchips from the beginning in the case of incentive absence;
- Gasification of the over-sieve material (compost out of specification) with and without the separation of the inert fraction (by means of a ballistic separator).

In this section, the minimum amount of incentive needed to reach an economic attractive investment condition for each technology and each material have been also evaluated.

Table 34 shows the benchmark data for each considered technology.

Table 34 Benchmark data for each type of technology chosen for the analysis [31]

		Technology 1	Technology 2	Technology 3
Cost of the plant	€/kW	4203.70	8333.33	4285.71
Maintenance	€/kWh	0.03	0.01	0.02
Personnel	€/kWh	0.02	0.03	0.02
Insurance	€/a	1366.67	10000.00	5683.33
GSE bureaucracy	€/a	1233.33	1000.00	1000.00
Biomass consumption	kg/kWh	1.04	1.17	1.04
Biochar production	kg/kWh	0.015	0.026	0.026
Module electric power	kW	45	148	125
Module thermal power	kW	100	289	250
Yearly hours of production	h/a	8167	7700	7800
Electric yearly energy	MWh/a	369.2	1065.0	937.9
Thermal yearly energy	MWh/a	833.3	1910.0	1644.2
Electric auto-consumptions	%	6%	17%	10%

The cost of biochar disposal is considered equal to 150 €/t, while according to data reported in the IDM paperwork an average price of the biomass equal to 94 €/t is considered (accounting for the purchase of a high quality and already dried woodchip).

4.3 Results of the analysis

The case of **bark introduction after incentives ending** with the aim of obtaining strong savings for the fuel purchase during the years of incentives absence have been evaluated. Fig. 65,66 and 67 show the results of the economic analysis performed according to the methodology described in the section 4.2, in terms of cumulated cash flow, for the technologies 1,2 and 3 respectively:
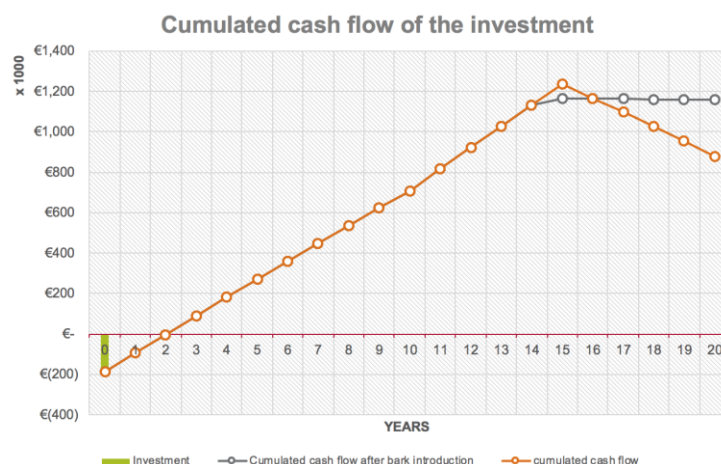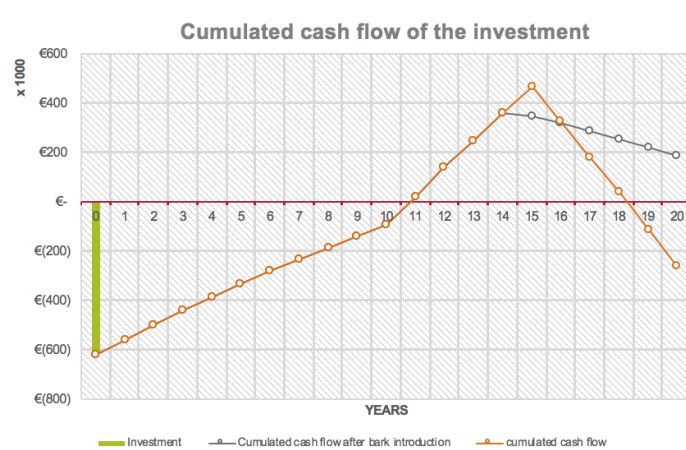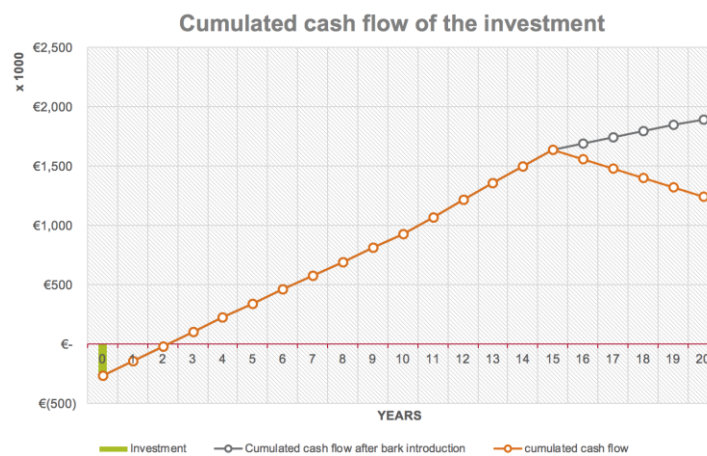

Figure 65 Technology 1

Figure 66 Technology 2

Figure 67 Technology 3

It can be noticed how, in presence of incentives (that for the chosen class of power of the plant was equal to 280 €/MWh) with all the technologies, the plant is payed back. In particular, technology 1 and 3 seems to be really competitive and attractive (Fig.65 and 67). The high cost of maintenance, biochar disposal and biomass cost produce a strong reduction of the incomes and thus a decreasing trend can be noticed during the last five years of plant expected life. For this purpose, the introduction of a 80% bark+ woodchip blend in the last five years of plant life, thus decreasing drastically the fuel cost seems to have a beneficial effect even if an additional investment for a dryer is needed (whose cost have been estimated starting from a unitary cost of 800 €/kW$_{el}$ according to information directly received from the company Spanner Re).

As already explained, the biochar production has been increased in order to take into account the different biomass nature starting from the data obtained in the laboratory.

In next case study the possibility of employment of the **bark and woodchip mixture in a plant from the beginning** of his life has been considered. The

evaluation has been performed considering the fact that at the state of the art no incentives are present.

For this reason, the value of minimum incentives that could guarantee a reasonable payback time has been also found.
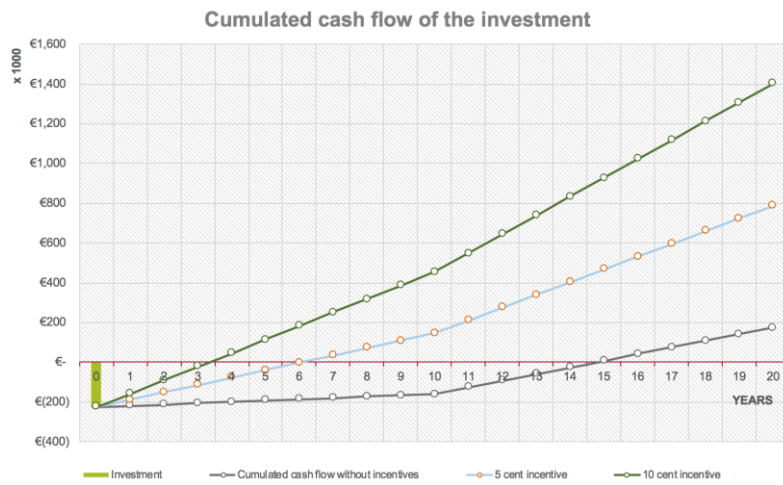

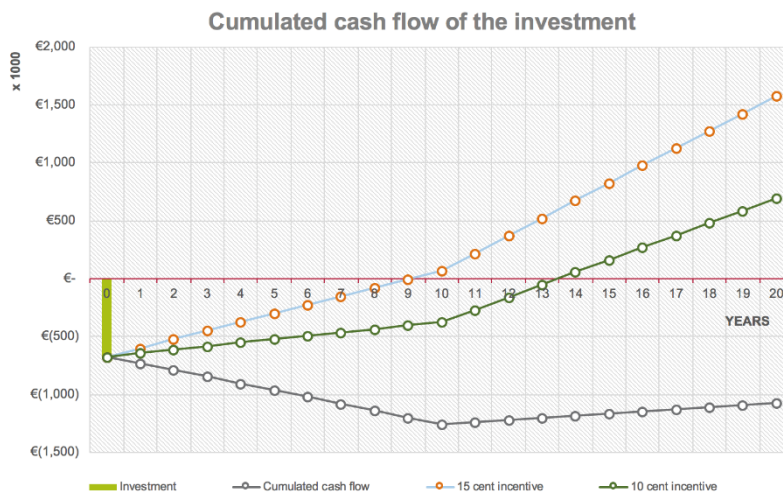Figure 68 Case of residues introduction from the beginning, technology 1

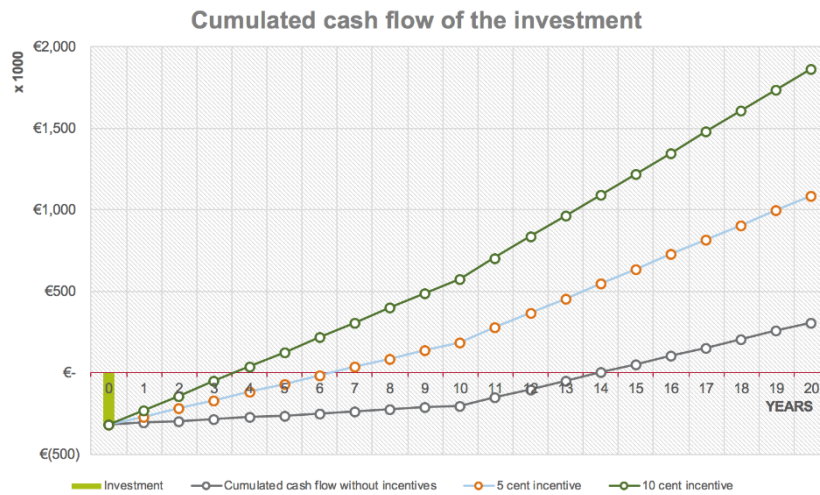Figure 69 Case of residues introduction from the beginning, technology 2

Figure 70 Case of residues introduction from the beginning, technology 3

Even in this case a strong difference between two of the three technologies has been found (technology 2 is never payed back during the plant life without incentives).

The result of the analysis shows how in the case of the employment of a residual biomass, 2 of the 3 technologies ensure the payback of the plant, which anyway occurs in the last years of the plant useful life.

The introduction of a much more smaller incentive respect last years (0,05 and 0.10 €/kWh$_{el}$ have been considered for the most favorable technologies and up to 0.15 for the most expensive one) ensures instead the possibility of a reasonable payback time.

In the case of an incentive of 0.05 €/kWh the payback occurs for 6-7 years and going up to 0.1 €/ kWh$_{el}$ the payback time becomes comparable with the actual condition of existing plants already exploiting incentives (0.28 €/ kWh$_{el}$). It can be noticed how most expensive technologies ensure reasonable investment conditions just with higher values of incentives (Fig. 69).

Compost out of specification employment case

As shown in the previous chapter, the most convenient case (from the energetic point of view) in the utilization of this material seems to be the one of inert separation. Thus the economic evaluation has been performed considering in the first case the entire material, and in the second case the separation of just the inert fraction.

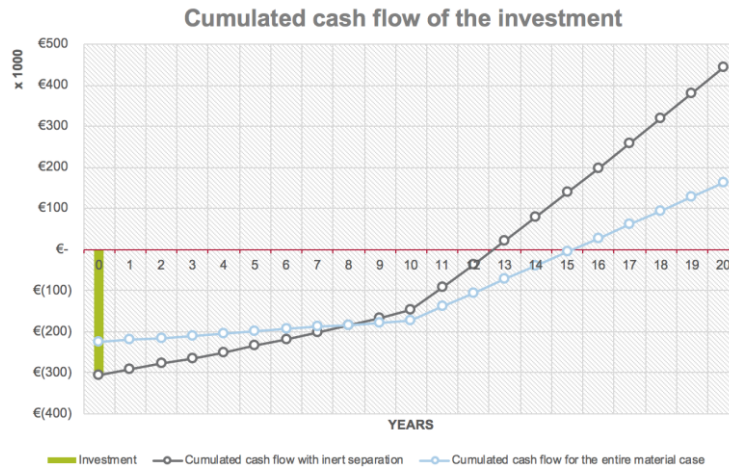A first comparison between the two cases is shown in Fig.71-73.

Figure 71 Comparison between entire material and inert separation case with technology 1
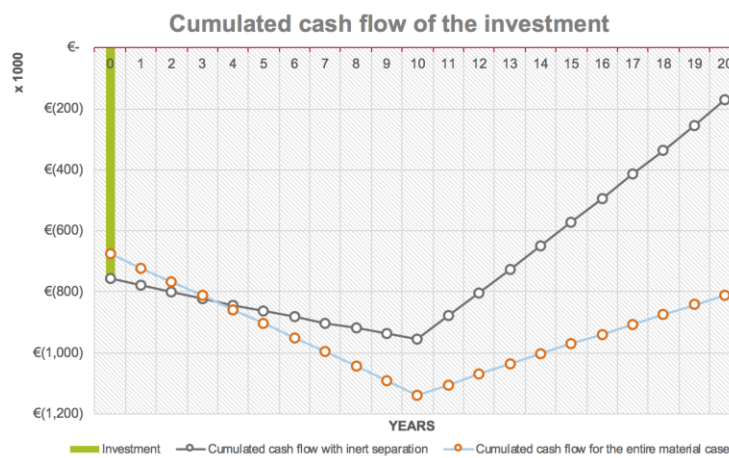

Figure 72 Comparison between entire material and inert separation case with technology 2
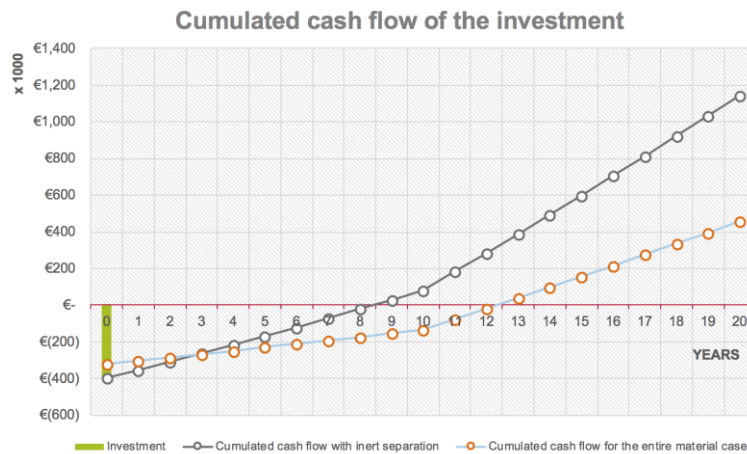

Figure 73 Comparison between entire material and inert separation case with technology 3

The separation of the inert part has been considered by means of the employment of a ballistic separator. The analysis considers a separator (with a unitary cost for the entire module of 160,000 €).

It can be noticed how, according to the analysis, the separation of the inert fraction is always positive in terms of economic results. This could be explained by the following main reasons:

- The inert separation ensures an increase of the LHV and a decrease of the ashes;
- The smaller ash presence (ashes in terms also of inert component) produces a reduction of the final biochar disposal.

It must be taken into account in fact that although the separation have a cost in terms of initial investment and power supply, the disposal of the separated inert have a cost of 50 €/t, while if the inert fraction takes part into the gasification process, the final disposal will cost 150 €/t.

The consideration of minimum incentives that could be ensured to this plants have been applied also in the case of this residue. The results of the economic analysis are shown, in terms of cumulated cash flow, in Fig.74,75 and 76 for the technologies 1,2 and 3 respectively.

Figure 74 Investment results in the case of entire material (left) and material without inert fraction (right) with technology 1 considering minimum incentives

Figure 75 Investment results in the case of entire material (left) and material without inert fraction (right) with technology 2 considering minimum incentives
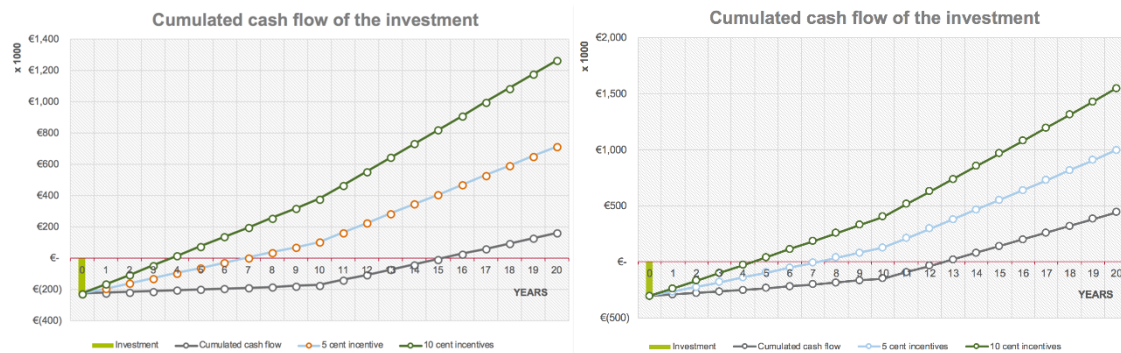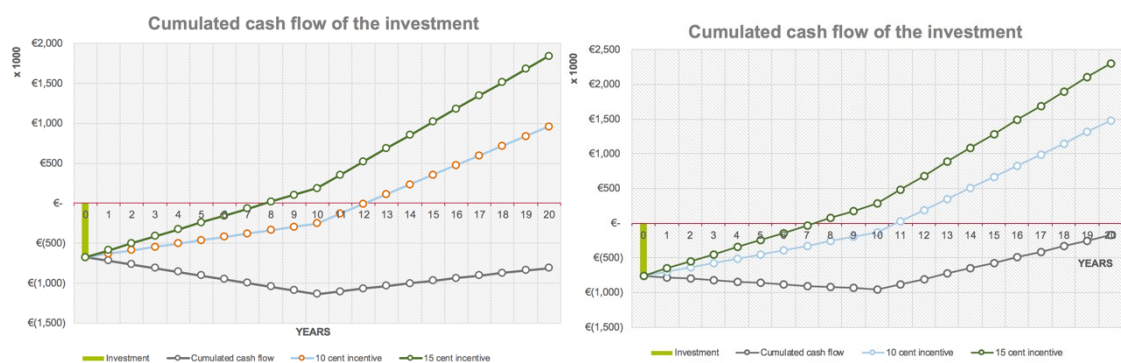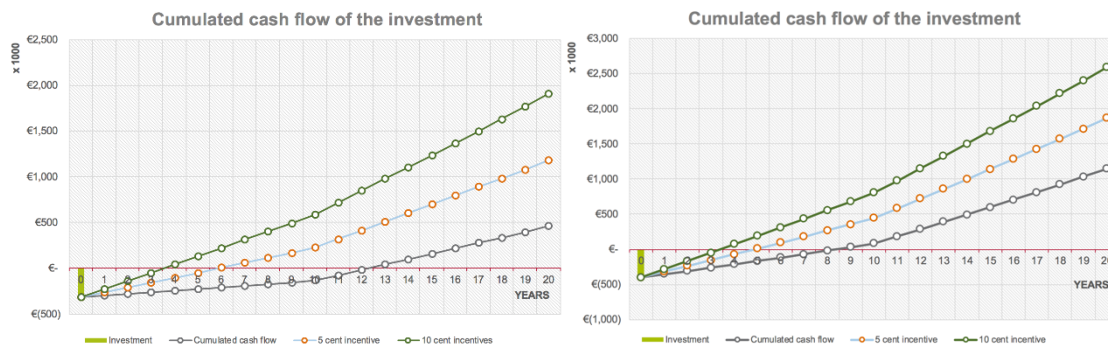
Figure 76 Investment results in the case of entire material (left) and material without inert fraction (right) with technology 3 considering minimum incentives

It can be noticed how the considerations expressed for the bark mixture stands also in this case. The two cases (with or without inert separation) are comparable on the long term.

The introduction of small incentives (0.05 and 0.10 €/kWh$_{el}$) would produce drastic reduction of the payback periods in the case of technologies 1 and 3, which could anyway be profitable (but not attractive).

Technology 2 seems to be affordable just in the case of higher incentives values (0.15 €/ kWh$_{el}$).

Finally, it must be highlighted the fact that this material is actually a waste product disposed in landfill, thus this kind of energy valorization could produce not only economic advantages for anaerobic digestion plants owners treating the municipal organic fraction, but could also drastically reduce the amount of landfill disposal of more than 50%.

Conclusions

The aim of this work was to study the possibility of an energy valorisation of biomass residues.

The residues considered in the analysis have been: agricultural residues (in particular the pruning residues of apple, grapevine, olive, pear, peach and citrus trees), barks (coming from the forestry industrial chain) and the compost out of specification produced in last sieving operations of the waste management plants treating the OFMSW and the green residues (leaf, pruning, branches from public and private gardens management).

An overview of the possible pre-treatments and conversion processes employed for biomasses has been proposed in the introduction.

The first step of the analysis has been the study of the quantities of each residue produced each year at national and local level. This procedure has been performed by means of three different methodologies (according to the residue considered).

The quantification of pruning residues has been performed starting from the data collected from ISTAT database (agricultural surfaces dedicated for each culture type) and applying literature coefficients expressing the average production of pruning residues in terms of t/ha. The results have been presented at national level, but a focus on each region, in particular Trentino-Alto Adige has been proposed.

The quantification of the bark production has been performed at regional level (for Trentino-Alto Adige region) starting from the procedures proposed by Emer et al. and Prando et al. considering the average annual trade price of a representative specie (Spruce), the data relative to the local production (acquired from ISPRA database) and the import and export trades (acquired from the Chamber of Commerce of the Bolzano province).

For what regards the over-sieve material (compost out of specification), a national analysis has been proposed, concentrating than the focus on a specific waste management plant placed in Trentino-Alto Adige region. The data relative to the national estimated production have been elaborated starting from the data provided by ISPRA and exploiting the specific information provided by the local waste management plant.

Of the three typologies of residues, two have been chosen to perform a deeper characterization and a techno-economic analysis: barks and the over-sieve material.

In the second part of the work, the characterization of the selected feedstocks has been performed. The bark samples have been collected, in local sawmill companies, while the compost out of specification have been collected in the

waste management plant, treating the OFMSW and green residues, placed in Trento.

The characterization tests have been performed in the laboratory of "Bioenergy & Biofuels Lab" of the Free university of Bolzano, and interested the moisture and ash content measurement, the elemental characterization and finally the HHV measurement. Also the thermogravimetric analysis of the bark samples have been performed in order to have a first access to the possible behaveiour of the ashes in the temperature ranges of the gasification process.

It must be highlighted the fact that, in order to have a reference for the gasification tests to be compared with the residue (barks) also an high quality woodchip have been analysed and gasified. Moreover, seen the heterogeneous composition of the over-sieve material, the different fractions detected in the over-sieve material have been analysed separately. Finally, also the possibility of the torrefaction pre-treatment have been evaluated. This evaluation has been carried out by means of the characterization and successive gasification of pellets and torrefied pellets.

The performed analysis highlighted the good energy properties of the barks residues, while a relatively small energetic content has been detected in the compost out of specification. In particular, considering the second material, the presence of an inert fraction and the high ash content has been noticed.

For what regards the torrefied pellet samples, the expected increase in carbon content and the higher energy content have been detected (in comparison with a standard pellet).

In the third part of the work, the gasification process of woodchips, bark and pellets have been performed. As mentioned, pure high quality woodchip has been employed with the aim of obtaining a reference for the bark residues samples, while standard pellet has been used as reference for the evaluation of the possible torrefaction pre-treatment. During the tests, also the possibility of air flowrate effect have been studied by means of the modulation of the secondary air feed in the char conversion zone.

The results of the gasification tests have been also used for the calibration of a thermodynamic model, employed for the gasification simulation of the over-sieve material (compost out of specification).

The gasification tests highlighted a comparable output (in terms of plant performances and syngas characteristics) in the case of the bark gasification with respect to the pure woodchips. An higher char yield has been noticed in the case of barks (justified by the higher ash content).

In the case of the torrefaction pre-treatment evaluation, the effect of the process during the gasification, seems to be not convenient from the energetic point of view, being the plant performances worst in the case of torrefied pellets with

respect to the standard pellet if the same conditions (in terms of secondary air) are considered. It must be highlighted the fact that, the torrefaction pre-treatment have been evaluated of a feedstock (pellet) that is already characterised by a good quality and energetic content, thus the results shown by residues could be different.

The general behaviour shown during all the gasification tests varying the secondary air feeding has been common for all the feedstocks. In particular the increase of the air flowrate in the char conversion zone always ensured an higher LHV of the syngas an higher CGE values.

The gasification process in the case of the compost out of specification have been simulated by means of the application of a thermodynamic model. The results in terms of syngas characteristics seems to be comparable with the ones obtained in the experimental tests with other feedstocks. As mentioned, the analysis proposed in this case is purely theoretical. The real utilization of this material (compost out of specification) in a gasification plant should be evaluated on the base of experimental tests with gasification reactors in order to draw more reliable conclusions.

In particular, the high ash content shown by the characterization results should be taken into consideration since it often represents a plant management problem in existing plants.

Finally, a techno-economic analysis have been performed considering the employment of barks and the over-sieve material. Three different technologies have been considered and chosen for their large diffusion. The three technologies considered are characterized by unit powers of 90 (2x45),148 and 125 kW.

In the case of bark employment, two different scenarios have been proposed: the first accounts for the possibility of substitution of the actual feedstock with barks (for the 80%) at the end of the incentive period for a plant switched on in 2012, while in the second case, the bark utilization from the beginning has been considered.

Considering the actual absence of incentives for the power production from biomass resources, the economic results obtained seems to be not always attractive. In particular, just two of the 3 techologies are payed back during the plant life.

For this reason, the "proposal" of minimum incentives (0.05, 0.10 and 0.15 €/kWh$_{el}$) guaranteed for this plants has been evaluated, showing results comparable with the actual state of the art in terms of payback times.

It can be said, that the exploitation of residues could represent a good economic chance for a future gasification employment considering the high of management, maintenance expenditures and the technology cost.

In the case of the over-sieve material, the analysis has been proposed comparing two different scenarios: one accounting for the utilization of the entire material and the one considering the separation of the inert fraction.

The results highlights the convenience of the inert fraction separation (as explained in fact, the separation upstream the gasification process allows the disposal of the inert fraction to a price that is three times smaller if compared to the disposal as residue product of the gasification process).

Even in the case of the over-sieve material, the absence of incentives does not ensures attractive payback times, thus the same minimum incentives considered in the case of barks have been considered, highlighting positive economical results.

In conclusion, the utilization or substitution of standard feedstocks in gasification plants could ensure positive economical results. Moreover, the needing of residual valorisation is crucial in a future optic of waste reduction. In particular, it must be highlighted the fact that in the case of materials such as the compost out of specification, the actual destination is the landfill disposal. This kind of energy valorization could produce not only economic advantages for anaerobic digestion plants owners treating the municipal organic fraction, but could also drastically reduce the amount of landfill disposal of more than 50%.

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