A HYBRID COMPOSTING AND HTC SYSTEM FOR THE MANAGEMENT OF THE RESIDUES OF THE ORGANIC FRACTION OF MUNICIPAL SOLID WASTE TREATMENT

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ABSTRACT

In this paper an innovative method of treatment of the digestate deriving from a municipal organic matrix is studied with the aim of re-evaluating from a energy and economic point of view a waste associated with socio-economic and environmental problems.

The pros and cons of the various existing biomass treatment technologies are analyzed, namely: composting, anaerobic digestion, pyrolysis, gasification and incineration.

The hydrothermal carbonization technology (HTC) is compared to other technologies and also deepened with regard to the chemistry of the reaction to better understand its functioning.

The model of an HTC system that should be installed in Poland is studied, to this end a research was carried out on the regulations in force in Poland concerning waste to energy.

Subsequently, a plant model was studied starting from the digestate reception to the exploitation of the output material, that is the hydrochar, with various plant assumptions.

An energy analysis is performed to make a forecast of the consumption of the plant and finally a financial analysis has been made with various scenarios to understand both the most profitable configuration from an economic point of view.

INTRODUCTION

Increasing population density along with a better quality of life have lead to high amounts of waste generated worldwide, resulting in several socio-economic and environmental issues. Globally, costs of solid waste management will rise from 205.4 billion per year to 375.5 billion per year in 2025[1], and these increases will especially affect low and middle-low income countries. Moreover, don't treat waste properly, usually results in higher down-streams costs than what it would have cost to handle it correctly. Another important aspect concerns the local and global impacts on the environment, solid waste is a source of methane, which is a Greenhouse Gas that is particularly impactful in the short-term. Municipal Solid Waste thereinafter MSW, have emerged as a post-consumer waste account for almost 5% (1,460 mtCO2e)[2] of total global greenhouse gas emissions.

Furthermore, there is a strong correlation between the improvement of wealth and the increase in energy consumption, it has been found that the direct influence of consumer activities in energy consumption equals to 43% of the total energy consumption[1]. A report from The World Bank[2] estimates that currently 1.3 billion tonnes of waste is generated per year all over the world and by 2025 this amount will increase to 2.2 billion tonnes per year. In order to develop a sustainable growth model in the EU, the European Commission, adopted the "Circular Economy Package" on December 2015[3].

This strategy aims at optimizing the consumption of resources, maximizing the permanence of goods and their value within the economic cycle (through re-use and recovery), also trying to reduce the production of waste to be disposed of.

In this scenario the recovery of organic waste through the production / transformation into soil improver to be used on agricultural land, ensuring fertility and promoting the production of edible crops can certainly be considered an example of Circular Economy.

Modern industry in Europe has shift towards to a series of thermochemical approaches that treating organic waste as a precious bioresource including gasification, pyrolysis and hydrothermal carbonization (HTC) method. Among the wet or hydrothermal treatments, HTC represents an innovative thermal process for the direct conversion of wet organic residues into a carbonaceous material, called hydrochar, which has a heating value higher than the original input material, with lower hydrogen/carbon and oxygen/carbon ratios and with a

chemical structure that make it similar to natural coal. This process is particularly interesting as it treats the wet material, eliminating drying costs, thereby making it attractive thanks to its energy-competitiveness compared to other processes. HTC works the biomass in high pressure vessel with liquid water applying temperatures in the range of 180-250 °C and with pressure of about 10-50 bar for some hours (0.5-8 h) in the absence of air[4][5][6]. This novel thermal conversion process with relatively low temperature is gaining significant attention as a sustainable and environmentally beneficial approach for converting waste biomass into value-added products.

Therefore in this introduction the aim is reviewing the existing technology employed for the treatment of Organic Fraction of Municipal Solid Waste (hereinafter OFMSW) in Europe, in particular this research assesses waste to energy technology which are classified as biological treatments (or Biochemical process) or as thermochemical treatments. Biological treatments are anaerobic digestion; aerobic processes or composting and combined anaerobic/aerobic treatment of OFMSW. Whereas common thermochemical treatments are pyrolysis, gasification, incineration and hydrothermal carbonization.

BIOLOGICAL TREATMENT TECHNOLOGIES

The OFMSW consists of organic materials from household like kitchen waste (food leftovers, etc.); garden waste (grass clippings, leaves, etc.) and also includes organic materials from municipality services (garden and park waste from municipalities, waste from maintenance of roadsides, if managed as waste; kitchen and canteen waste)[7].

In nature, the conversion of organic matter is carried out by many microbial communities such as bacteria, fungi. The bacteria are monocellular heterotrophic organisms, classified into aerobic (if oxygen is necessary for life), anaerobic (when they can live in both previous conditions) which have to be feed to grow and multiply, using the outside organic substances that they are not able to synthesize themselves. Performing these functions involves energy consumption. Biological treatment processes exploit the needs of bacteria to use organic nutrients and organic energy substances to meet their needs. Biological treatment technologies (BTT) are designed and engineered for natural biological process working with the organic rich fraction of MSW[8]. These treatments are divided into two different processes according to the conditions in which happen: the aerobic process or composting which leads to the formation of a solid fraction called compost, an organic soil improver with numerous advantages from an environmental and agronomic point of view; and the anaerobic process which has a combustible gas consisting in a mixture of methane and carbon dioxide as its main output. The last process requires less energy than the aerobic process and creates much lower amounts of biological heat. The biodegradable fraction is converted into a fuel known as biogas[8]. This biogas is burned to produce heat and/or electrical energy[9].

COMPOSTING TECHNOLOGY

Composting is the biological degradation process of organic matter in an aerobic environment, with the aim of transforming the raw waste into a biological stabilized material, called compost. The organic fraction is converted by a microbial community into more stable, humified forms as well as water, carbon dioxide and ammonia, releasing heat as a metabolic waste product[10]. The resultant compost is a stable, humus-rich, complex mixture that can improve physical properties of the soil. Compost originating from the organic fraction of municipal solid waste (OFMSW) is increasingly used in agriculture as a soil conditioner as well as a fertilizer. Almost 50% of the whole amount of compost produced in Europe is used in agriculture and is

regarded as a way forward to address both security of nutrients and organic matter supply thus improving soil conditions[11]. The characteristics of the compost vary according to both the type of waste subjected to stabilization and the process conditions: when only the vegetable fraction is used, it is called a composted c; while when it is obtained from a mixture of vegetable and wet domestic fraction, it is referred to a mixed composted soil improver. In both cases, the legislation[11] sets the requirements that the compost must have in order to be used in agriculture.

Composting process phases

Composting process can be divided into three phases, namely initial activation, thermophilic and mesophilic or maturation phase[12]. During the thermophilic phase, microorganisms degrade the majority of the organic waste. In this phase microbial catabolism of organic waste release heat to the composting pile and the high temperature achieved is also crucial for pathogen reduction and sanitization of organic waste. The Environmental Protection Agency (EPA)[13] guidelines require composting material to maintain a temperature of 55 °C for at least 15 days or 5 consecutive days. The decrease in temperature establishes the end of the thermophilic phase and the beginning of the maturation phase. The temperature will continue to decrease up to ambient temperature and marks the exhaustion of decomposable organic fraction in the waste. The duration of the process was dependent on the composting system and scale of the process.

The effectiveness of the composting process is influenced by factors such as temperature, oxygen supply (i.e. aeration), moisture content, pH, C/N ratio, particle size and degree of compaction[14].

Temperature is one of the main parameters for monitoring the composting process in addition of being a function of the process. Temperature is a significant factor in determining the relative advantage of some microbial population over another. This could be attributed to the effect of temperature on the physicochemical characteristics of composts and subsequent bioavailability of the substrate to the composting microorganism[15]. Therefore the temperatures of the composting mass indicate the rate of degradation of the organic matter and in real-time shows the establishment of optimal conditions that facilitate microbial degradation[16].

An optimum initial C/N ratio of organic waste is necessary for the growth of microorganisms, indeed some research[17] have shown that high C/N ratio will limit the composting rate as there is an excess of degradable substrate for the microorganisms. Instead with lower C/N ratio

there is an excess of nitrogen per degradable carbon and inorganic nitrogen is produced in excess which can be lost through ammonia volatilization. Achieve the desired C/N ratio it's possible by mixing different types of organic waste and this will improve composting efficiency as well as regulate moisture content[18].

Moisture content (hereinafter MC) is a critical parameter in the composting process. It influences the oxygen uptake rate, free air space, microbial activity, and temperature of the process[19]. As MC increases, the rate of gas diffusion declines, and the oxygen uptake rate becomes inadequate in meeting the metabolic demands of the microorganisms. During composting, the MC is vital for distribution of soluble nutrients needed for the microbial metabolic activity[20]. Furthermore, loss of moisture during the composting process can be counted as a strong indication of decomposition rate. It was observed[21] that there was an inverse link between MC and temperature; as the temperature became elevated, MC decreased.

Aeration is a procedure which allows the material to be more available to the microbial activity. The most common method is the rotation of the materials, but the rotation regime must be optimized in order to retain the relevant nutrients in addition to increase the reduction of pathogens. Indeed a better aeration reduces the stabilization duration in the early stages of organic degradation, yet an excess of turning can lead to the death of vital components for composting.

Aeration is an important factor influencing composting[15]. Fundamentally, composting is an aerobic process, in which O_2 is consumed, and gaseous H_2O and CO_2 are released[16]. Aeration rate affects the quality of the compost since influencing compost stability and also influence the efficiency of the process because the composting process is directly associated with microbial population dynamics[22]. The authors also explained that too little aeration can lead to anaerobic conditions, and as well excessive aeration can result in excessive cooling, thus preventing thermophilic conditions required for optimal rates of decomposition.

The pH level is an important parameter in the composting process that under optimal condition support microbial decomposition on a range of 7/8[23]. According to previous studies[24], changes in pH may be indicative of biological activity. It also made it known that microbial activities become limited when the pH is outside the optimal range.

Other research[25] noted that increase in pH caused an increase in NH3/NH4 ratio resulting in increased volatilization rates.

PH increase can result from the accumulation of ammonia resulting from the degradation of

proteins furthermore it has been noted that pH as a factor that influences composting sometimes is not independent of temperature[26]. This may be attributed to the existence of different microbial groups at different combinations of temperature and pH.

The particle-size distribution of the final compost is important because it determines gas and water exchange, and especially water-holding capacity[27]. Particle size has a great influence on the maintenance of adequate porosity for proper aeration. Particle size of substrates for composting should not be too large as they will decompose slowly. The particle size should also not be too small as they can form a compact mass and reduce the porosity of the compost substrate[28]. The principal method for determining particle size distribution is sieving.

Composting technology[29]

Composting in heaps (open piles)

The organic material is placed in heaps of trapezoidal or triangular section, placed outdoors in appropriate areas of a drainage system for rainwater and runoff. The plant must also provide for proper oxygenation of the material, for example by means of a mechanical shovel or automatic turning machines. In the past this has been the most used system, but it is preferred that the process takes place in closed spaces, in order to avoid the diffusion of unpleasant odors.

Static aerated batteries

The waste is disposed in heaps (pile) covered with mature compost that has the purpose of acting as a biofilter for odors. In this case the batteries are not moved by air through appropriate perforated pipes placed underneath the material.

Composting in a closed reactor

The bioxidation phase is performed inside a closed reactor, where the material is subject to intense transformation processes. The reactors are always of the static type (biocells) if the material does not undergo the handling during the phase of bioxidation, or provides for the turning of power by screw feeders or the revolution of the digester itself (rotary drum reactor).

Benefits of composting

Composting has received increasing attention as an environmentally acceptable way to dispose of and utilize organic wastes which are usually incinerated or deposited in landfills . Composting has been shown to be effective in reducing relatively persistent organic compounds such as veterinary pharmaceuticals[30]. For instance the product of composting,

(compost) has also been found to have many benefits such as a better quality than commercial inorganic fertilizers[31]. According to previous studies[32] composts can replace soil conditioners in support of humus formation, which is a benefit that cannot be achieved artificially. Temperature build-up during composting has resulted in elimination of pathogenic organisms in waste. The authors[33] also acknowledged the contribution of compost to improving the water-holding capacity of soil.

It is also well-known[34] that composting is a sustainable process in terms of economic aspects as it involves lower operating cost as compared to other waste management options. The low cost involved is due to low technical complexity and capital requirements.

Problems of composting

Composting is typically a time consuming process, but advancement in composting technology has reduced the duration of composting process. It has been shown[35] that additives, such as jaggery and polyethylene glycol, helped hasten the composting process as well as produce superior quality compost, however these additives are not economically viable.

The purpose of composting is to convert organic waste into fertilizer material, but certain organic waste contains high concentrations of heavy metal contents that are not removed during composting process[36]. Generally, total heavy metal contents will increase after composting process owing to the reduction of organic matter.

Emissions of significant amount of greenhouse gases (GHGs) during composting processes are leading to secondary pollution such as greenhouse effect, thus mortifying the environmental benefits of the process. As was stated[36], losses of carbon (C) and nitrogen (N) during composting process will reduce the agronomic value of the compost. GHGs are released due to the energy needed by the composting facility (i.e. machinery used) and by the biodegradation process itself which produces CO2, methane and nitrous oxide. Most C is lost as CO2 while methane accounting for <6%[36], which are two of the most important GHGs in the atmosphere.
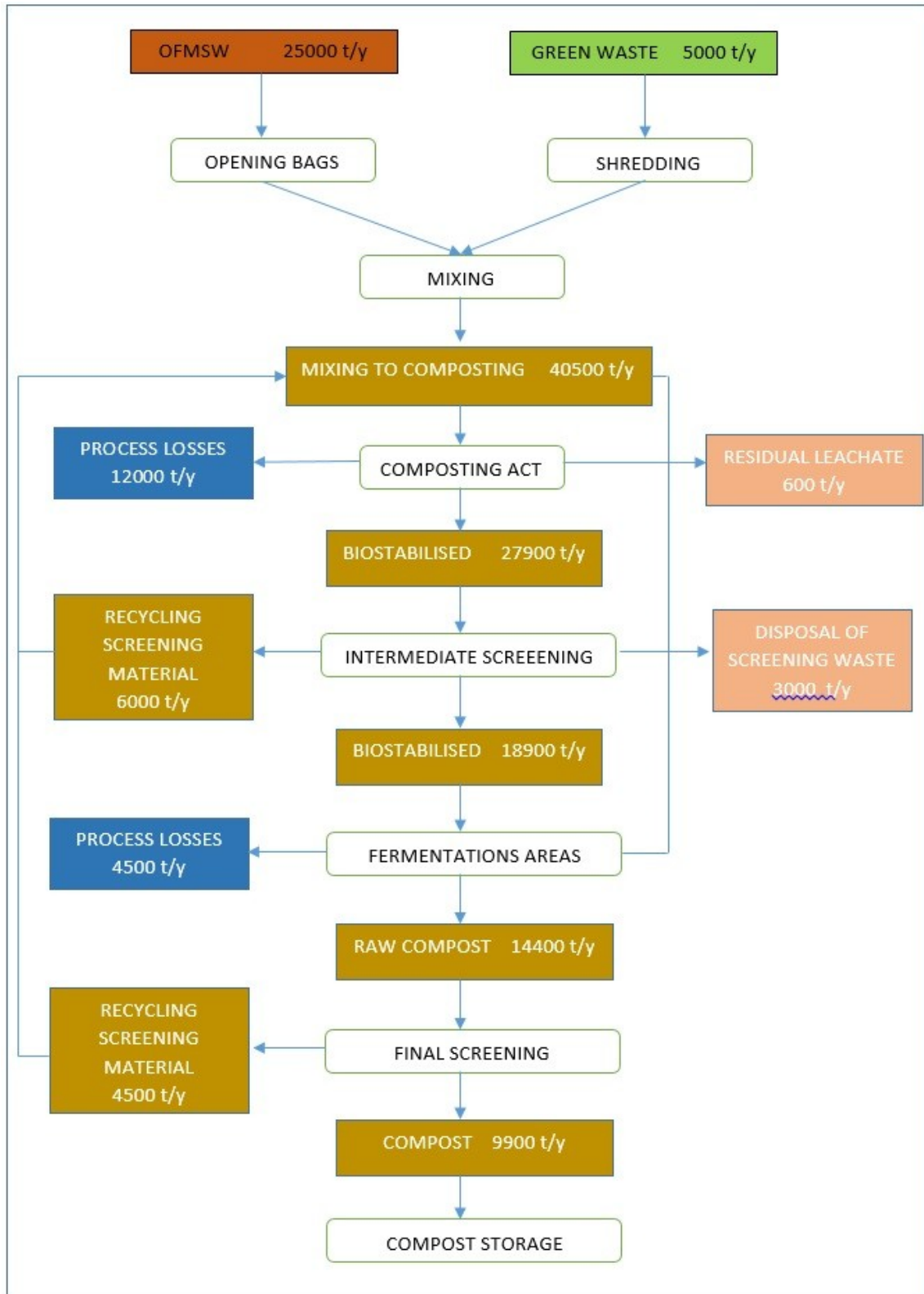
Figure 1 flow chart for material balance composting plant with 40000 ton/y capacity

ANAEROBIC DIGESTION TECHNOLOGIES

Anaerobic digestion is a technology for the treatment of organic waste in absence of oxygen and in presence of anaerobic microorganisms. This technology is mainly used for its ability to produce methane as a source of renewable energy, as well as being interesting in the recovery of nutrients such as Nitrogen and Phosphorus, which from an environmental and economic point of view are a key factor as they allow to use the digestate as a fertilizer.

Technologies

The Anaerobic Digestion technology (hereinafter AD) as part of biological waste treatment, can be used[37] to process OFMSW, in particular the organic fraction mechanically separated from mixed MSW using mechanical–biological treatment (hereinafter MBT) plants and to process source separated organics (SSO understood as kitchen waste collected directly by the inhabitants) .

Depending of total solids (hereinafter TS) concentration of the material which undergo AD can be classified into 'wet', 'dry' and 'solid state' processes, however wet and dry technologies are mainly used for AD of OFMSW. Wet AD operated with TS < 15% and generally, have been adopted in well-established systems to treat municipal wastewater. Dry AD operated with TS < 25%, higher solid content than the wet AD. The main output from AD are a biogas mainly rich in CH4 (about 60% volume per volume), CO2 (about 40% volume per volume) and a a digestate rich in nutrients and organic carbon with a MC usually > 80% weight per weight[38].

The production of biogas reduces the amount of waste and, therefore, reduces the amount of waste to be disposed off in landfills. Biogas is usually used in two ways: to generate electricity and to produce heat in different required processes. Excess heat can be additionally used in district heating networks or in industrial processes; and future studies regarding the use of biogas as vehicle fuel are expected[39].

Anaerobic digestion in Poland

Polish legislation defined the process conditions for the organic fraction mechanically separated from mixed MSW at MBT plants with AD or stabilization under aerobic conditions.

Currently as reported by Central Statistical Office 2015[40], in Poland 95% of the OFMSW is treated with MBTs in aerobic conditions. Slowly diffusion of AD plants is due to the fact that the biogas produced it is not considered energy recovery nor is it qualified as a renewable energy source, so there is no remuneration for green electricity.

Other types of municipal waste are kitchen and garden waste that directly feed the AD or alternatively are composted.

Green waste, on the other hand, is not treated with AD because this technology is not effective with too lignocellulosic biomasses.

It seems that in Poland, the biggest challenge is recycling of OFMSW in particular the SSO from which depend the potential for AD plants and therefore from the involvement of inhabitants in the process of source separation also to reduce the level of landfilling of biodegradable waste.

Within a circular economy context, the AD technology seems to be an essential element able to create new process links to form a sustainable cycle using renewable resources to produce energy and make fertilizers.

As far as economic efficiency is concerned, it is mainly influenced by the gate fee, other evaluation components are the remuneration for the green energy generation, as well as operating and maintenance costs (O&M) for waste pre-treatment and digestate after treatment. Costs for processing OFMSW in MBT with AD process were estimated to be in the range of 60-90 €/ton for gate fee while we are on 75-120 €/ton for processing in AD plants with SSO[39].

The costs of O&M vary greatly depending on the methods of post-treatment, in fact if the digestate can not be used for agricultural purposes the costs for its further treatment either by landfilling or by incineration increase dramatically.

The biogas produced is converted into electricity and used for the self-consumption of the plants, while the excess is sold to the grid. Such plants also produce heat that can be used for personal purposes or sent to district heating systems.

In addition to the economic issues, another problem concerns social acceptance and the distance between the treatment plants and the inhabited areas, as far as Poland is concerned, it can be concluded that a distance of almost 1 km from the inhabited areas is required, taking into account the AD plant with MBT located in Gac (Poland). Another problem is related to the emissions of odors, particularly if the plants is located in urban areas, that can be limited by airtight systems, which, however, increases costs.

In Poland, where GDP per capita is below European average and there are problems with source separation, investments can be expected mainly on AD plants with MBT. However, with the increasing level of separate collection, the adopting of AD plants with SSO may

increase.

In the assessment of this operation, logistics, waste pre-treatment and post-treatment must be considered. The aspect of internal policies regarding the sale of by-products such as electricity, heat, digestate and compost must also be considered.

According to the estimates of the Central Statistical Office 2015[40], up to30% of OFMSW will be treated anaerobically and 70% aerobically, by 2020. In the best case, it will be possible to reach 50% of AD understood as MBT to 2030. However, in the perspective of 2030 there will be more and more market opportunities for the AD plants with SSO and for this to take place a development of an efficient separate collection system at source, meaning directly at he household site, is inevitable.

The above is preconditioned by a well functioning legal framework, a strong commitment by the authorities and an educational activity to involve the members of the community members in the process.

COMBINED ANAEROBIC/AEROBIC TREATMENT OF OFMSW

As reported in the previous paragraph, anaerobic digestion is one of the most common options for the organic fraction of municipal solid waste (OFMSW), expecially when collected separately. Anaerobic processes allow the production of biogas that can be used as a renewable energy source. Along with digestate with a potential fertilizing value is producted, but it must be treated with complex and expensive machinery because of its possible phytotoxicity.

A possible solution to this problem has been found in the post-aerobic treatment of the digestate, which allows to obtain a stabilized anaerobic by-product in order to improve its fertilizing properties. The treatment of the OFMSW as a combination of anaerobic and aerobic treatment therefore allows to get the production of both energy from methane and a fertilizer from the digestate[41].

Due to the high technological complexity of these plants, constant monitoring of the process is needed to ensure proper process yields[42]. Researches[43] claim that mass balances are the most suitable tools for managing plants that treat organic waste.

To this end a full-scale facility treating source separated OFMSW located in the municipality of Salerno (Italy)[44], with a design capacity of 30 000 tons of waste/year was considered in the study. Mass balances were carried out in terms of dry matter, volatile solid content as well as compostable materials.
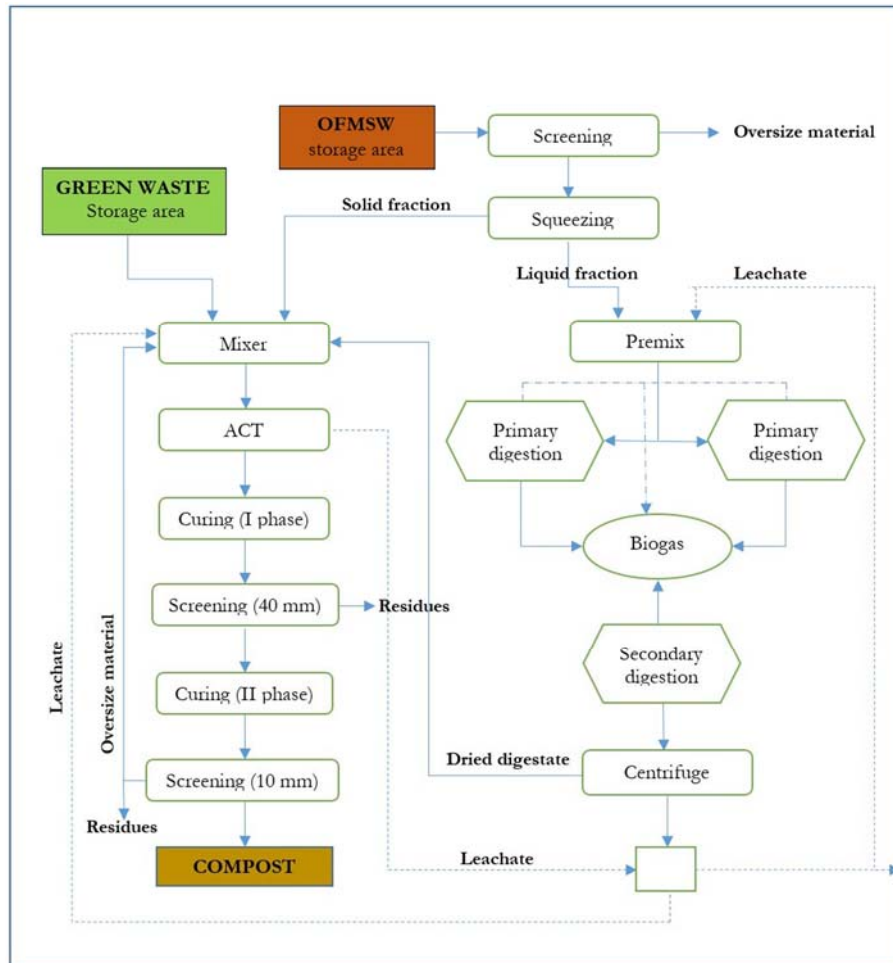
Figure 2 flow scheme of integrated anaerobic / aerobic digestion plant

The source sorted OFMSW is pretreated trough a screening operation that aims at retaining all impurities from the incoming waste. The selected material is then directed to the squeezing stage: the organic matter is processed into an extrusion chamber which relies on very high pressure to let the fluidized organic material (liquid fraction) squeezing out of the chamber through the extrusion holes.

The liquid fraction is then used for energy production in the anaerobic digestion process while the solid one is addressed to the aerobic stabilization phase along with the dried digestate produced from the anaerobic process.

The squeezed organic fraction destined to anaerobic digestion usually represents the 40% of the pretreated waste. This liquid fraction is characterized by a very low total solid content, comparable with the one of sewage sludge, thus allowing the simplification of mechanical systems (i.e. pumping systems) of the anaerobic digestion section, with a consequent significant decrease in both capital and operating costs.

The liquid fraction is pretreated in a premix tank, aimed at both the sedimentation of possible inert and the anaerobic process activation.

The anaerobic treatment is implemented through two primary digestion tanks working in parallel and a secondary digestion tank.

The average retention time of the treated material is 11 days in the premix tank, 43 days in the primary digestion tanks and 22 days in the final digester. Therefore, the whole anaerobic treatment is characterized by an average duration of 76 days.

The solid fraction originated from the squeezing process, accounting for the 33% of the incoming OFMSW, is directed to the aerobic phase, along with the following substrates:

- the green waste, accounting for approximately 30% of the treated OFMSW;

- the undersieve resulting from the compost refining phase, representing almost the 8% of the incoming OFMSW;

- the dried digestate which accounts for the 2.5% of the treated OFMSW;

- the leachate, which is discontinuously recirculated in order to ensure the optimal moisture content for the biomass under composting. It is expected to be equal to the 22% of the incoming OFMSW.

The composting process is divided in two stages: the active phase (15–20 d) carried out through biocells and the curing phase realized using aerated windrows. The latter step is further divided into two different ones: the organic matter is first processed using passively

aerated windrows for 15–20 d (primary curing) and then sieved before being directed to mechanically turned windrows, whose treatment lasts up to 65 d (secondary curing).

The aerobic process cycle lasts almost 95 days, so that the whole biological process has a duration of about 170 days, which is recognized to be useful to reach an adequate biostabilization level. The integration of anaerobic and aerobic processes is gaining increasing interest for the treatment of source sorted OFMSW. The combined treatment ensures the recovery of energy from the biogas along with the production of compost which can be used as soil conditioner. However the complexity of both plant chart and involved processes requires an accurate monitoring activity, which can be supported by appropriate mass balances. Thanks to this mass balance it has been observed that a considerable part of the organic matter (30%) has been removed together with the impurities with a consequent loss of biogas and therefore of important reduction of energy generation.

THERMAL TREATMENT TECHNOLOGIES

PYROLYSIS

Pyrolysis is the thermochemical decomposition of organic material at high temperature in the absence of oxygen and it has been used for centuries as a thermochemical conversion process in the production of charcoal. The recent developments of this technology make it possible to use it to process organic waste for energy recovery, and of particular interest is the flexibility to generate a combination of solid, liquid and gaseous products in different proportion just by varying some operating parameters such as temperature or heating rate. This process permit to transforms materials of low-energy density into bio-fuels of high- energy density and recover higher value chemicals[45].

The liquid from the pyrolysis process is known as pyrolysis oil or bio-oil, and it can be used for fuels or feedstock for many commodity chemicals. In terms of fuels, the oil can be used without an upgrading process in many applications including boilers, furnaces, diesel engines, and turbines for the generation of electricity[46]. In addition, the greatest advantage of pyrolysis oil compared with fossil fuel is that the use of this oil contributes minimally to the emission of greenhouse gases[47]. Nevertheless the fuel characteristic of it remains lower than fossil fuel, especially with regard to combustion efficiency, indeed the high composition of oxygenated compounds in pyrolysis oil is responsible for this problem. Several researchers have reported that oil from the pyrolysis of biomass generally has an oxygen content of around 35–60%[48] and this high level of oxygen in pyrolysis oil creates a low caloric value, corrosion problems and instability. Improvement in the quality of pyrolysis oil is important to assist and provide a solution for several challenges in its applications. Many upgrading techniques have been taken into account and among them, catalytic cracking and hydrodeoxygenation are the most commonly used techniques. Catalytic cracking is a method that involves the addition of a catalyst to the pyrolysis process, and hydrodeoxygenation is a suitable way to convert low grade pyrolysis oil into hydrocarbons. However, catalytic cracking produces high quantity of coke (8-25%)[49] during the process and also there are some problems associated with catalyst such as the increasing level of solid residues, which have to be disposed; the short life cycle of the catalyst due to deactivation and the fact that using a catalyst increases costs. Moreover, also the hydrogeoxygenation[50] has problems concerning the complexity and the costs because of the complicated equipment, the need to add catalysts, and the high-pressure requirements

for the reaction.

Pyrolysis processes on the basis of heating rate can be classified as slow pyrolysis, fast pyrolysis and flash pyrolysis. Slow pyrolysis that employs a relatively slow heating rate 45- 50°C/min and long residence time of about 1 hour[51], causes a reduction of liquid yield and maximize the solid product yield. Fast pyrolysis employs a high heating rate of 10-200 °C/s, short hot vapour residence time of approximately 0.5-10 s and rapid vapour cooling to maximise liquid yield, in fact to maximize pyrolysis liquid yield the temperature should be in the range of 352-452 °C to obtain about 40-75% of liquid bio-oil[52]. For flash pyrolysis, the heating rate occurred at rate higher than 1000 °C/s with very low residence time of less than 0.5 s.

The reactors used for conventional pyrolysis of MSW are mainly rotary kilns and tubular reactors, in particular for up-scaled facilities, whereas fixed-bed and fluidized bed reactors have been frequently used for lab-scale studies[53].

Pretreatments such as shredding and drying are often required, especially for heterogeneous MSW fractions. The currently available pyrolysis plants for MSW treatment at demonstration and commercial scales are generally operated in combination with gasification or combustion systems. Operation of stand-alone pyrolysis is still under development for MSW treatment to produce liquid and char as end products[54].

GASIFICATION

Gasification is a thermochemical conversion from carbonaceous materials into syngas (mixture of H2 and CO), tars and biochar at high temperature (>500 °C) in oxygen deficient conditions[55]. According to types of biomass and the compositional matrix of the final products, different gasifiers are used, in order to optimize energy from different feedstocks. In general gasifier could be classified in three major types: fixed bed, fluidized bed and entrained flow. Gasification generally produces more energy per unit mass of carbonaceous material because of its high conversion efficiency of carbon compared to fast and slow pyrolysis[56]. Furthermore gasification provides self sustaining energy support for reactions and electricity and heat production can potentially be used in feedstock-related upstream or biochar-related downstream treatment process. Gasification is suitable for small and medium scale decentralized systems which have lower carbon conversion rates[56].

The gasification process generally involves four consecutive steps: drying, pyrolysis, partial oxidation and reduction[57]. Drying occurs at 100–200 °C and the moisture content of biomass is reduced to <5%. Pyrolysis (or devolatilization) consists mainly in the thermal decomposition

of the dried solid fuel in the absence of oxygen or air, being the volatile matter reduced, releasing hydrocarbon gases and (if condensation at low temperatures occurs) liquid tars. The pyrolysis reactions are endothermic and the heat needed is supplied from the oxidation reaction. Oxidation is the reaction between solid carbonized biomass and oxygen in the air, resulting in the formation of CO2. The hydrogen present within the biomass is also oxidized, generating water. CO may be generated if oxygen is present in substoichiometric quantities and carbon is partially oxidized. The overall heat required for endothermic reactions is supplied by this oxidation process. Reduction (or gasification) occurs between 800 and 1000 °C, in the absence or sub-stoichiometric presence of oxygen, because the oxygen is consumed in the oxidation process. The final products of these reactions are mainly gas mixtures including hydrogen, carbon monoxide, carbon dioxide and methane.

Among the thermal conversion process, gasification requires specific fuel characteristics such as low heating value, and low moisture and ash contents. Therefore waste and biomass used as a feedstock must undergo a pretreatment process, consisting of shredding, screening, sorting, drying, and torrefying, pelletizing or briquetting[54]. Without pretreatment sector the gasification fuel is not heterogeneous so the quality of the final product as well as the operating conditions can be compromised.

Another weak points of utilizing raw biomass and wastes as a fuel for WtE conversion is the moisture content, as it defines the amount of energy spent for drying the feedstock. Generally, reduction of biomass moisture content allow to increase energy efficiency, improve syngas quality and lower conversion emissions[54].

Other problems[58] arise from flue gases from gasification in fact contain particulate matter, acidic gases (e.g., nitrogen oxides and hydrogen chloride), and organic pollutants such as dioxins. In addition, the final process residues with potential leachability of heavy metals and organic pollutants represent a major environmental concern. The emissions of these pollutants are nowadays controlled by end-of-pipe technologies such as electrostatic precipitators, bag filters, and the addition of slaked lime but the costs required for syngas conditioning and cleaning in gasification-based MSW treatment is higher than that for MSW incineration.

Finally another big issue[59] is the formation of tar substances, which is a mixture of condensable high molecular weight hydrocarbons that can potentially lead to blocking, fouling, and corrosion. Tar removal can be achieved by different methods including physical (e.g., filters, scrubbers, and wet electrostatic precipitators) and chemical processes (e.g., thermal and catalytic cracking). The resulting char from the incomplete combustion of the

biomass is also a large issue as it causes reactor plugging. One method of improving the gas quality and reducing tar and char contents is to utilize different gasification agents and catalysts.

Challenges and perspective

Thanks to the ability of biochar to sequester carbon and the benefits of applying biochar for agricultural purpose with high persistence in soil environments, change the perspective of gasification, indeed new biochar applications is developing. The most economically sustainable gasification system will achieve a balance between energy output and biochar generation, under which some consideration[55] are needed: (1) the source of gasification feedstock (waste or biomass), (2) the syngas yield, composition, and applications (3) biochar yield and its physicochemical properties and applications, and (4) the respective carbon abatement potential of applying syngas as a renewable energy and applying biochar as a renewable source. In the future, it is worth exploring novel and unconventional biochar application scenarios and using LCA to optimize the combined economic and environmental performance of gasification systems. Hence, it is critical to understand the influences of feedstock and thermochemical conditions towards the properties and performance of gasification biochar.

Other challenges exist in the disposal of the gasification product residue. Due to the abundance of metals present in the solid residue, this by-product causes concern for aquatic ecosystems and landfilling sites. However, if the metals in the solid residue can be isolated and recycled or reused, this would substantially decrease the negative impact of the gasification process.

INCINERATION

Incineration is a thermal conversion in which waste is directly burned in the combustion chamber at high temperature (750-1100 °C)[60] and in presence of oxygen.

The aim of the process is to reduce the weight and the volume of the MSW and the production of energy and heat within a cogenerative system. In Poland up to the end of 2016 there are 7 incineration plants located in Warsaw, Krakow, Poznan, Bydgoszcz, Szczecin, Konin and Bialystok which produced approximately 527000 MWh of electricity and 836000 MWh of heat[61].

Net energy yield depends on density and composition of waste, on the relative percentage of moisture and inert materials, on ignition temperature, on size and shape of the constituents

and on the design of the combustion system. The incineration is suitable for heat and steam production from MSW. Usually, the electric energy is produced by a turbine connected to a generator and the heat by a district heating system. The energy efficiency for generation of heat, cogeneration (heat and electricity), and pure electricity is ranges from 80%, 20–30% and 20% respectively[62].

Conventional incineration technology usually includes these operational steps: reception of incoming waste; storage of waste and raw materials; pre-treatment of waste; loading of waste into the process; thermal treatment of the waste; energy recovery and conversion; flue gas cleaning; flue gas cleaning residue management; flue gas discharge; emission monitoring and control; waste water control and treatment (from site drainage, flue gas treatment, storage); ash/bottom ash management and treatment; solid residue discharge/disposal.

The combustion temperature of conventional incinerators are about 760°C in the furnace and in 870°C in the secondary combustion chamber, in order to avoid odour due to the incomplete combustion, but some modern incinerators reach temperature of 1650°C using auxiliary fuel to reduce waste volume by nearly 97% and convert some inorganic contents such as metal and glass to inert ash[63].

The highest environmental impact of MSW incineration is the production of pollutant emissions causing public health concerns. In the state of art an additional treatment is needed before the final emission of the flue gas in the atmosphere to reduce the amount of specific emissions such as: sulphur dioxide, hydrogen fluoride, nitrogen oxide and nitrogen dioxide, total organic carbon, hydrogen chloride, carbon monoxide, dust and volatile heavy metal[64]. Some researches[63] investigates way of treating ash from waste to energy facilities. Ash consists of residues left in the combustion chamber and in their pollution treatment devices (fly ash). The main aim of ash treatment is to prevent the toxic constituent of the ash especially dioxins, furans and heavy metals from escaping into environment after disposal. The main residue from MSW incineration is slag and the amount depends on the ash content of waste. In addition to the slag, the plant generates residues from dry, semidry or wet flue gas cleaning process. Much of the slag may be used as road construction material after sorting. Another disadvantage from incineration concerns heavy investments and high operating costs thanks to the complexity of the plants which require skilled staff, furthermore, residues from flue gas cleaning can contaminate the environment if not handled appropriately.

On the other hand, some advanced technologies have been developed to reduce these effects. For example, a hybrid plant using incineration and gasification has been developed to reduce

volatile heavy metals[65].

HYDROTHERMAL CARBONIZATION (HTC)

Among the thermochemical conversion processes, HTC converts wet biomass into a solid product, called hydrochar. The process is performed in conditions of relatively low temperature 180-250 °C and with a pressure between 10-40 bar which allows to keep the water in liquid phase[5][66].

This new process is gaining significant attention as a sustainable and environmentally friendly approach to converting waste streams into value-added products. Indeed, the organic fraction of municipal solid waste is characterized by high humidity, low calorific value and can also cause unwanted interactions during conventional treatment processes such as central incineration and landfilling.

Modern European industry sees organic waste as a precious resource and uses thermal treatments such as gasification, pyrolysis and among these processes HTC allows to operate without a drying pre-treatment step.

Comparison between different hydrothermal treatment

Hydrothermal treatment can be divided into four main types as hydrothermal carbonization (HTC), hydrothermal liquefaction (HTL), hydrothermal gasification (HTG) and aqueous phase reforming (APR) based on different products and relevant conditions.

HTG and APR focus on the production of H2 which is a substance with many applications but the cost of the catalyst and the rigid reaction conditions do not allow these technologies to emerge on a large scale. Instead, both HTL that has a bio-oil output (mostly organic acids and sugar), and HTC from which a solid product is obtained (hydrochar) are very promising because they operate in relatively mild conditions where the addition of catalyst is not necessary, therefore they are more practical for industrial treatment[67]. In particular, the high conversion rate from feedstock to hydrocarbons and the milder reaction conditions of HTC among other HT treatments have attracted a high interest in this treatment.

Difference between HTC, pyrolysis, gasification

In order to maximize the heating value and the added value of recovery products after gasification, pyrolysis or HTC, energy is maintained into a solid product known as "biochar" or "hydrochar"[68]. HTC is a wet process, which uses humidity as a means of heating, unlike

gasification and pyrolysis, there is an important energy saving because drying pre-treatment step is not needed for the feedstock, moreover HTC work in a closed system in saturation conditions and energy costs for heating water are much lower than those for evaporating water in traditional processes[5]. Lower energy costs and lower operating temperatures make the process more environmentally friendly and also reduce CO2 emissions[69].

The hydrochar properties shows less stable structure due to the greater presence of alkaline groups compared to the biochar dominated by aromatic groups, but have a better ability to retain nutrients.

Chemical reaction during HTC

During hydrothermal carbonization (HTC), the biomass undergoes a series of reactions that rearrange its structure providing solid (hydrochar), liquid and gaseous products[69]. The reaction mechanisms are interconnected with each other and occur simultaneously and include hydrolysis, dehydration, decarboxylation, aromatization and recondensation[6].

Hydrolysis has the lowest activation energy and therefore will be the beginning of the HTC process. In this first phase the chemical structure of the biomass is broken through the splitting of ester and ether bonds of bio-macromolecules with water molecules[70]. Saccharides and lignin fragments are created (oligo-) that enter the liquid phase. The latter are then hydrolyzed into phenols, but saccharides may continue to initiate other pathways and chemicals during HTC. Dehydration is the process in which water is removed from the biomass, eliminating the hydroxyl groups. Decarboxylation is the removal of CO2 from biomass, eliminating the carboxyl groups in the process. Aromatization occurs due to dehydration and decarboxylation. Double-bond functional groups such as $C = O$ and $C = C$ replace the single-bond hydroxyl and carboxyl groups in the biomass matrix. The furfural compounds generated by these two mechanisms then undergo hydrolysis, which further separates them into acids, aldehydes and phenols. The acids that are generated then catalyze the release of inorganic elements from the biomass matrix.

The compounds created during the mechanisms described above can undergo a recondensation if they are highly reactive. Lignin fragments are highly reactive and easily condense, as well as aromatized polymers from cellulose degradation. The recondensation of the degradation products of HTC leads to the formation of hydrocarbons[71]. Hemicellulose

degradation products, however, stabilize the lignin fragments and significantly slow down the condensation reactions.

Properties of initial feedstock

The OFMSW as previously described consist mainly of organic matters, such as agricultural residuals, food waste and yard waste, contain large amounts of water and high content of carbon. An analysis composition of OFMSW shows that the carbohydrates is the most abundant component account for more than 40% in terms of dry basis[67]. Carbohydrates compounds are mainly cellulose, starch and glucose and generally follow hydrolysis and carbonization stages, during which optimal reaction conditions to receive ideal char properties has been studied. The hydrochar produced from OFMSW suggests both dehydration and decarboxylation occur during carbonization, though an agreement on formation mechanisms has not been reached. Some experiments[72] proves that different organic waste as feedstock generates hydrochar with different properties, inter alia increasing carbon percentage of initial feedstock produce an improvement in the carbon content and energy density of hydrochar.

Among all types of organic waste, food waste (FW) with relatively high initial carbon retention and mostly underutilized fraction may be the most ideal material for energy-related with HHV that can be reach 25 MJ/kg[73][72].

Effects of HTC conditions on hydrochar production

The results of previous research[5][72] indicate that the composition of HTC products is related to the reaction conditions, both physically and chemically. Studies have been carried out by varying the temperature range and residence time and by adding chemicals that modify the quality of process water such as catalysts. The analysis of the process is therefore focused on how the conditions of the process affect the hydrochar and on uncertainty related to certain materials such as metals and nutrients.

Temperature

Temperature is one of the most significant parameters on the result of HTC reaction. A higher temperature accelerates the dissolution of feedstock, but also the decomposition of products.

The hydrochar generated by OFMSW tends to retain more stable thermal compounds within the solid residue, because, when the temperature increases, the amount of volatile compounds decreases. From the mass balance and on the basis of the comparative results[72] it is noted that when we are close to 300 ° C, there is more volatile matter that is converted into a fixed carbon

and a small portion of other substances as liquid or gaseous.

With the increase in temperature it is also observed that lower H/C and O/C atomic ratios of waste derived hydrochars which indicates higher decarboxylation and dehydration reactions.

However, the optimal temperature for HTC is always balanced by energy densification (HHVchar / HHVfeedstock) by multiplying hydrochar yield as energy recovery efficiency[72]. For organic waste containing large amounts of biomass fractions, a higher temperature is required even if the energy content of the hydrochar produced could be further increased by the addition of biomass.

Residence time

Residence time has showed less significant impacts on HTC products in accordance with temperature-related change. Though reported[74] residence time varies from hours to days, unlike pyrolysis, there is no obvious evidence that solids yields increase with increases in residence time. However there is the hypothesis[72] that a longer reaction time may correlate to greater energy, which can be recovered from the gas-phase thus maximize the production of energy-favorable hydrochar.

Carbon enriched char for co-combustion as energy supplement

Hydrochar generated by the HTC process at high temperature (250 °C) from food waste and lignin waste have high energy density comparable to lignite. In addition to the enrichment of carbon content, the HTC process from lignin waste provides better hydrophobicity and a reduction of alkaline and alkaline-earth in the metal content.

Due to the dehydration and drying properties of hydrochars, it is possible to separate the liquid phase after the HTC in large quantities, this allows to have a net calorific value greater than that which must undergo the phases of dehydration and drying.

It has been shown[72] that in the co-combustion of lignite and hydrochar, both types of hydrocarbon addition have improved energy conversion by increasing burnout, breaking loads and shortening the combustion range of the mixtures. The HTC process shows high rates of pollutant removals in the co-combustion process such as potassium, sodium and chlorine[75], however, hydrochar washing may be required to avoid ash problems when it used as fuel.

Highly functional carbon material as soil amendment for carbon storage

Approximately less than 10%[5] of the carbon is released as gas (mainly CO_2) after HTC process of OFMSW. Therefore, less emission of CO_2 is released during HTC comparing to other

treatment of OFMSW because of limited expose to oxygen if the hydrochar is used as a soil amendment for carbon storage.

Industrial application of HTC treatment

HTC is a promising technology and has been listed as a feasible approach in several conducted European projects aiming at the converting of waste substrates into biofuel production for renewable energy supply, i.e. BIOBOOST project (2015) and NEWAPP project (2015). Furthermore the combustion of hydrochar as alternative fuel is the main application of in-used industrial HTC plants.

Pending problems during industrial application of HTC

The aqueous phase from HTC is one of the main drawbacks of hydrothermal process. The liquid intermediates represent 20-37%[75] of initial carbon remains in the liquid. For instance, the resulting process water from agro-waste has a high Total Organic Content that can be further utilized by biogas generation plants.

After appropriate treatment like wet oxidation of the process water it could be used to heat up the reactor or introduced in the process for reaction optimization.

Therefore, another option to increase carbon yield in hydrochar and in heat recovery system is the extraction of valuable chemicals and recirculation in the aqueous phase[76]. However the complexity of process water composition made it challenging to identify each individual organic component[77], thus caution is needed when is reused in an irrigation system or discharged during industrial HTC application.

Summarizing recent progress of the HTC process with OFMSW:

(1) the chemical properties of feedstock are fundamental for understanding the carbon content that remains in the produced hydrochar. In fact, OFMSW with high initial carbon content is excellent for producing high energy hydrochar.

(2) extension of residence time and the reaction temperature are very important to improve the properties of hydrochar as solid yield, ash/carbon content and energy density. In particular the temperature plays a key role with the enrichment of carbon.

(3) hydrochar can be used as energy supplement and as soil amendment. This last use allows to reduce the environmental impact and to limit the emissions of gas.

(4) the main industrial application for OFMSW treatment is the combustion of hydrochar generated by HTC, moreover also the co-combustion of lignite and hydrochar shows

interesting results.

The main problems for HTC industrial application are the energy spent on heating process and the use of process water. So we are trying to develop a hybrid HTC system for OFMSW that can improve the current technology.

LEGISLATIVE CONTEXT OF MUNICIPAL SOLID WASTE MANAGEMENT IN EUROPE

In Europe an action plan was adopted in 2015 to develop a circular economy[78], in which the consumption of waste and resources must be minimized, keeping the value of products, materials and resources as long as possible.

With this perspective Europe community moves from a linear economy system summarised as taking, producing, consuming, dispose of and shift toward a model of consumption and sustainable development that is in line with the EU's commitments under the 2030 Agenda for Sustainable Development. All this translates into the diffusion of renewable energies, improvement of energy efficiency, greater independence of resources, economic opportunities and long-term competitiveness.

With regard to waste, seeing them as a potential energy source can be the key to a circular economy, so we try to develop waste to energy which includes various waste treatments, from which we derive electricity and/or heat, or a fuel derived from waste can be produced. The management of municipal solid waste should then be sustainable and also economically advantageous and socially accepted, also because an efficient urban waste management system is a symptom of a better overall waste management. Speaking of management, waste follows multilevel governance since the route is provided by the EU but is implemented at national level through national plans, then regional plans are formed and finally local authorities shall implement and organize tools for the collection, treatment and disposal. Governments are very important in developing new technologies that would find hard to survive without their support. These technologies are in fact facing a hard struggle when they are commercialized because they do not yet benefit from scale and learning economies, and supply chains and market structures are not yet established. In addition to economic difficulties, another problem that WtE must face up, can be summarized with the acronym NIMBY (not in my backyard) that includes the problems of local citizenship, as risks perception, noise, smells, opinions on the benefits provided by WTE. Therefore risks and actively involve the public and businesses in the management process, such as willingness to recycle, must be communicate. Another key point is to educate and raise public awareness and to defend the potential of MSW as an energy resource.

An example of collaboration between research centers and ministries such as environment

and energy between member states can be found in the project "RECO Baltic 21-Tech" partly funded by the Program for the Baltic Sea region 2007-2013, is an example of mutual benefits on universities, research centers and companies on waste management problems in the Baltic Sea regions such as Poland, Lithuania, Estonia, Latvia, Sweden and Germany. Finally, therefore, having in mind the circular economy model to be developed, all obsolete treatment systems should be eliminated, moving to more intelligent systems that contain this approach.

The notion of msw more clarity from EU

The Waste Framework Directive introduces new concepts of "by-product" and "end of waste" with the aim to tighten the scope of waste. For example, now a waste substance can be reclassified as by-product, at EU and national level.

As far as biomass is concerned, since it can be considered as a renewable resource, it is regulated by the European Renewable Energy Directive, known as RED. Biomass is then defined as "biodegradable fraction of products, forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste". The biodegradable or organic fraction of municipal solid waste includes food waste from restaurants, households, farmers' markets, gardens, textiles, clothing, paper, and other materials of organic origin. Clear and predictable definitions set by EU are necessary to ensure an efficient reporting and monitoring system.

MSW management: EU requirements

To translate the principles of EU waste legislation at national, regional and local level, it is necessary to plan. The European Commission declares that a large part of the energetic potential contained in waste streams is lost in the EU economy. To improve the efficiency of resources and to continue the transition to a circular economy, the European Parliament set the most ambitious targets for those proposed by the European Commission in March 2016, indicating the target of reuse and recycling of municipal solid waste to at least 60% by 2025 (including a minimum of 3% of total municipal waste prepared for re-use) and at least 70% by 2030 (including a minimum of 5% of total municipal waste prepared for re-use). Parliament also demands that at most 5% of MSW be sent to landfills in 2030 and also urged the Commission to set targets for reducing food waste.

Waste to energy in the circular economy

The direction taken by the EU is clearly that of prevention, re-use and recycling, focusing on separate collection systems and increasingly reducing the energy obtained from mixed waste

or taxing incinerators. These principles are mirrored by the WtE technology which also fall within the emission reduction parameters. Biomass, which includes the biodegradable part of urban waste, is therefore encouraged by the RED to become an increasingly important source of energy. Including organic waste to potential renewable energy sources has allowed member states to achieve their national targets, in fact statistically biomass and waste in Europe are 63.1% of the total share of renewable energy sources[79]. In the Commission published in November 2016 the "Clean Energy for the Europeans" strategy called "Winter package", where the eight legislative instruments are concerned, the Commission recommends a new target of at least 27% renewables by 2030[80].

MSW management in Poland

Currently, municipal waste management in Poland, which entered into force before entering the EU, in 2004, is governed by the following acts: Act on Keeping Cleanliness and Order in Municipalities[81] which requires the municipality to organize an efficient waste collection, transport and treatment system; Environmental Protection Law[82]; Act on Obligations of Businesses in Management of Certain Wastes and on Product Fees[83]; Act on Waste[84]; Act on Packaging and Packaging Waste Management.

In 2015, 10.9 million tons of urban waste were produced (282 kg per capita), equal to about 8% of total waste. It is noted that the amount of waste has been decreasing in recent years, however this decline can be attributed to factors such as: the lack of measurement equipment; fly-tipping of waste, or the domestic combustion; insufficient control by the municipalities; reduction in the weight between waste collection and weighing.

In Poland, in fact practices such as combustion in the boiler are very frequent, because from the user's point of view it's free energy, compared to the relatively high cost of coal (around 150 E/t).

In 2015, the Chief Inspectorate of Environmental Protection issued permits to import a total of 253000 tonnes of waste from the EU and 40000 tons from other countries. The largest quantity of waste imported into Poland came from Germany and Lithuania. On the other hand, 194000 tonnes of waste were exported from Poland, mainly to Germany[85].

MSW management and organisation: Poland

In Poland there are 2479 municipalities where each one is responsible for organizing and managing MSW through selective collection, even if these data also apply to municipalities that have a two-bin system, dry and wet, showing low efficiency. In 2017 the waste tax can

not exceed 7€ per person per month, moreover it can not exceed 2% of monthly disposable income. Very important is the fact that the waste tax depends on whether the waste is separated or not, motivating residents to separate waste. In Poland, the Act on Keeping Cleanliness and Order in Municipalities allows a common tender for the collection and disposal of waste, preventing the municipality from controlling the flow of waste entering the disposal plants. The situation is not the best in Poland, as the landfill is still the main form of waste management, moreover companies can receive waste from residents for payment in proportion to the quantities discharged, unfortunately some improper entrepreneurs use this situation to illegally get rid of the waste.

Fortunately, the financial efforts[86] made to improve waste management are bearing fruit. Recycling in recent years is approaching the EU average level and there is a gradual decline in landfilled waste. This trend is very promising and Poland will probably reach the recovery and recycling rates required by 2020, which are specified in the Environment Ministry's regulation of 14 December 2016. With regard to biodegradable waste, it has been established that by 2020 the mass of such waste directed to landfills should not exceed 35% of the mass biodegradable waste, which was produced in 1995 equal to 4.38 million biodegradable MSW. Objective achieved in 2014, with 1.53 million tons of this waste in landfill[87].

The last national waste management[87] plan 2015-2022 establishes the main objectives for the management of urban waste, summarized in the following key points:

1) reduce waste generation and improve public awareness of proper waste management;

2) achieve the assumed levels of recovery and recycling for particular types of waste;

3) increase the proportion of waste collected selectively by covering all residential properties with a system of selective collection of municipal waste;

4) stop disposal (storage) of biodegradable waste selectively collected and mixed municipal waste without treatment.

Waste to energy in Poland

In the European context also Poland considers the Waste to Energy a necessary requirement to move from the landfill to higher levels in the waste hierarchy. It is a key issue also because Poland is forced to produce 15% of its energy from renewable sources in 2020 and it is estimated that about 50% of the energy produced by waste can be considered renewable. The percentage of energy from waste, compared to renewables up to a few years ago was 0.5% but the recovery of WtE technology will become very important in the green energy market,

especially in terms of heat production. For example, until 2015 there was only one incineration plant in Poland with a capacity of 60000 t/y, definitely too low to meet the needs. The Polish market is focusing mainly on two innovative projects, the first being "Innovative technological process of converting waste into high quality solid fuels" (co- financed by the Smart Growth Operational Programme for the period 2014-2020) aims to carry out activities of industrial research to promote an innovative conversion of organic waste into high quality solid fuels and obtaining biocarbon from organic waste with low energy consumption. In addition, a project[88] is proposed to develop and validate the conversion of organic waste into biochar. This technology will have two innovative aspects, namely the concept of bio-sequestration of carbon from waste and the original concept of integration of thermochemical processes in the proposed technology that leads to the disposal of waste and the production of valuable and innovative biochar. The second project, financed by the same program, concerns "high-performance gasification", a biotechnology of sludge and organic waste (industrial and municipal) that uses a co-fermentation process to produce biogas and organic-mineral products and to generate heat and electricity . This technology is still under development to make it flexible through compact modules with integrated multifunctional cascade reactors, together with control units.

PROCESS MODELING

In this paragraph, a method to search reaction enthalpies of HTC process has been implemented using a Matlab model. The method and data to develop the model have been derived from previous research[89] that will be summarized below. Firstly, a general stoichiometric equation has been used to describe the process, its also possible to express in terms of chemical formulas the whole reaction, after making some assumptions such as the composition of the liquid phase which is composed by 5-hydroxymethylfurfural (5-HMF), phenol and water. The enthalpies of formations of the process molecules derived from literature data and from group contribution methods calculations. Enthalpies has been calculated at different reactor working conditions, varying temperature and residence time to see how they affect the reactions. Finally a graphic of reaction enthalpy has been shown, in order to understand if the process is endothermic or exothermic.

FORMULATION OF THE PROBLEM

The whole reaction can be expressed in the general stoichiometric form:

$$FS \rightarrow HC + LPC + H_2O + GAS$$
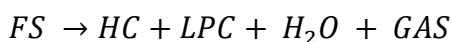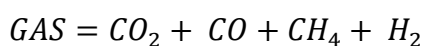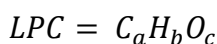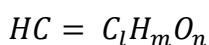
where:

FS, is the feedstock

HC, is the hydrochar (solid phase product)

LPC, is a liquid pseudo-component

H_2O, is the water formed during the process

GAS, is the gaseous phase

It is possible to express the equation in terms of chemical formulas:

$$FS = C_xH_yO_z$$

$$HC = C_lH_mO_n$$

$$LPC = C_aH_bO_c$$

$$GAS = CO_2 + CO + CH_4 + H_2$$

thus obtaining:

$$\alpha C_xH_yO_z \rightarrow \beta C_lH_mO_n + \gamma C_aH_bO_c + \delta CO_2 + \varepsilon CO + \epsilon CH_4 + \theta H_2 + \vartheta H_2O$$
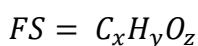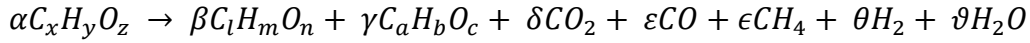
As suggest by (Basso, 2016) to assess the $\Delta H_f°$ of each chemical compound, it is possible to state the following reactions, while for gaseous phase data is available from literature[90].

Feedstock equation for standard enthalpy of formation:

$$C_xH_yO_z + hO_2 \rightarrow xCO_2 + \frac{y}{2}H_2O + \frac{z+2h-2x-y/2}{2}O_2$$
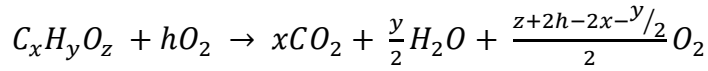
$$\Delta H_{f,298}°(C_xH_yO_z) = x \cdot \Delta H_{f,298}°(CO_2) + \frac{y}{2} \cdot \Delta H_{f,298}°(H_2O) - Q(C_xH_yO_z)$$

where,

$$Q(C_xH_yO_z) = HHV(C_xH_yO_z) \cdot \text{(molecular mass of } C_xH_yO_z)$$

Hydrochar equation for standard enthalpy of formation:

$$C_lH_mO_n + jO_2 \rightarrow lCO_2 + \frac{m}{2}H_2O + \frac{n+2j-2l-m/2}{2}O_2$$
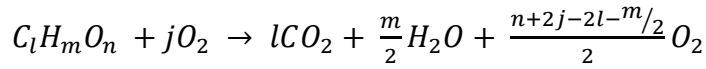
$$\Delta H_{f,298}°(C_lH_mO_n) = l \cdot \Delta H_{f,298}°(CO_2) + \frac{m}{2} \cdot \Delta H_{f,298}°(H_2O) - Q(C_lH_mO_n)$$

where,

$$Q(C_lH_mO_n) = HHV(C_lH_mO_n) \cdot \text{(molecular mass of } C_lH_mO_n)$$

Liquid pseudo-component equation for standard enthalpy of formation:

$$C_aH_bO_c + kO_2 \rightarrow aCO_2 + \frac{b}{2}H_2O + \frac{c+2k-2a-b/2}{2}O_2$$
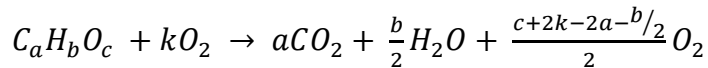
$$\Delta H_{f,298}°(C_aH_bO_c) = a \cdot \Delta H_{f,298}°(CO_2) + \frac{b}{2} \cdot \Delta H_{f,298}°(H_2O) - Q(C_aH_bO_c)$$

where,

$$Q(C_aH_bO_c) = HHV(C_aH_bO_c) \cdot \text{(molecular mass of } C_aH_bO_c)$$

Gaseous phase for standard enthalpy of formation:

The following data shows the standard enthalpy of formation of the gaseous phase

$\Delta H_{f,298}°(CO_{2\,(g)})$ [kJ/mol]	-391,51
$\Delta H_{f,298}°(CO_{(g)})$ [kJ/mol]	-110,53
$\Delta H_{f,298}°(CH_{4\,(g)})$ [kJ/mol]	-74,52
$\Delta H_{f,298}°(H_{2\,(g)})$ [kJ/mol]	0

An unified correlation[91] for estimating HHV of solid, liquid and gaseous fuels.

$$HHV_{dry} = 0.3491\,X_C + 1.1783\,X_H + 0.1005\,X_S - 0.1034\,X_O - 0.0151\,X_N - 0.0211\,X_{Ash}$$

HHV_{dry} is expressed in MJ/kg and X_i are the mass percentages on dry basis of each element.

IDENTIFICATION OF MOLECULES

The experimental data used in this discussion are those obtained through the HTC of grape seeds. These experimental data are reported in a research article[89] and show the different composition of the products of the reaction HTC under various operating conditions, ie varying the residence time of the product in the reactor (1, 3, 5 h) and the reaction temperature (180, 220, 250 ° C).

The information needed to calculate the standard enthalpies of formation of the process are:

- Process product yields of HTC process in terms of amount of hydrochar, liquid and gas at different process conditions

- Results of the ultimate analyses corresponding on the weight fractions of C, H, O, N and Ash by the mass of feedstock or hydrochars, evaluated at different temperatures.

- Data of liquid and gaseous phase in terms of Total Organic Content (TOC) for liquid phase; in terms of amount molar percentage in the gas phase of CO_2, CO, CH_4 and H_2;

- Numbers of moles of C, H and O within the phenol and 5-HMF.

In order to simplify the evaluation of the standard enthalpy of formation of the liquid phase content the mole of C have been divided proportionally between phenol (54%) and 5-HMF (46%), in this way reaction equation can be written as:

$$\alpha C_x H_y O_z \rightarrow \beta C_l H_m O_n + \mu C_6 H_6 O + \pi C_6 H_6 O_3 + \delta CO_2 + \varepsilon CO + \epsilon CH_4 + \theta H_2 + \vartheta H_2 O$$
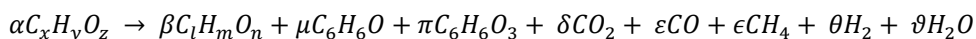
where $\mu = 0.54 \cdot C_{TOC}$ and $\pi = 0.46 \cdot C_{TOC}$, where C_{TOC} represents the number of moles of carbon measured within the liquid phase, through the determination of the TOC.

STANDARD ENTHALPIES OF FORMATION

Feedstock's standard enthalpy of formation

Using the data reported in research article[74] and considering a molecular mass of one pseudo-mole of feedstock of 100 g/mol, this mole will consist of

C [$g_C/mol_{molecule}$]	54,4
H [$g_H/mol_{molecule}$]	6,6
O [$g_O/mol_{molecule}$]	34,2
N [$g_N/mol_{molecule}$]	1,6
Ash [$g_{Ash}/mol_{molecule}$]	3,2
S [$g_S/mol_{molecule}$]	0

considering $\Delta H_{f,298}°(H_2O_{(l)})$ = -241.81 kJ/mol it's possible to solve the equation in order to find the standard enthalpy of formation of feedstock material:

$\Delta H_{f,298}°(C_x H_y O_z)$ = -215.57 kJ/mol.

Hydrochar's standard enthalpy of formation

Hydrochar's standard enthalpy of formation has been calculated using the equation described at paragraph 4.1 and the heating values have been obtained from previous research[74] according to (UNI EN 14918, 2010). Table below reports the HHV, the stoichiometric coefficients and the standard enthalpies of formation of the hydrochar, evaluated at the different process conditions.

T [°C]	τ [h]	C [wt%]	H [wt%]	O [wt%]	N [wt%]	Ash [wt%]	HHV [kJ/g]	fmC_hydro [mol]	fmO_hydro [mol]	fmH_hydro [mol]	Hf_ClHmOn [kJ/mol]
180	1	60.240	6.62	27.84	1.32	3.98	25,847	5,0154	1,7400	6,5678	-182,94
	3	60.600	6.50	27.43	1.40	4.07	25,871	5,0453	1,7144	6,4487	-177,98
	8	62.300	6.80	25.35	1.40	4.15	27,031	5,1869	1,5844	6,7464	-153,63
220	1	63.400	6.70	23.96	1.60	4.34	27,434	5,2784	1,4975	6,6472	-137,38
	3	63.600	6.40	23.75	1.60	4.65	27,165	5,2951	1,4844	6,3495	-134,80
	8	68.400	6.70	18.28	1.90	4.72	29,754	5,6947	1,1425	6,6472	-69,173
250	1	66.500	6.40	20.54	1.80	4.76	28,504	5,5365	1,2837	6,3495	-95,918
	3	69.500	6.60	16.99	1.90	5.01	30,148	5,7863	1,0619	6,5480	-53,872
	8	70.700	6.50	15.66	2	5.14	30,582	5,8862	0,9787	6,4487	-37,756

Table 1 HHV, stoichiometric coefficients and the standard enthalpies of formation of the hydrochar

Hence, the average standard enthalpy of formation $\Delta H_{f,298}°(C_l H_m O_n)$ has been calculated:

$\Delta H_{f,298}°(C_l H_m O_n)$ = -115.94 kJ/mol.

Liquid pseudo-component's standard enthalpy of formation

As previously described, phenol and 5-HMF were taken as representative of the liquid compounds formed during HTC, which remain dissolved in water at the end of the process, according to previous research[89]. As a matter of fact, data on the standard enthalpy of formation of phenol are available in literature[90]. Thus, the Benson group contribution method[90] was used for the determination of $\Delta H_{f,298}°(5\text{-}HMF)$.

Thus, $\Delta H_{f,298}°(C_6 H_6 O)$ = -96.4 kJ/mol and $\Delta H_{f,298}°(C_6 H_6 O_3)$ = -277.2 kJ/mol.

Finally, considering the distribution of the two chemical species within the liquid (54% phenol and 46% 5-HMF), the average standard enthalpy of formation of the LPC can be assessed:

$\Delta H_{f,298}°(C_a H_b O_c)$ = -179.6 kJ/mol.

ENTHALPY OF THE HTC REACTION

In this paragraph, the calculation of the enthalpy of reaction at the HTC operational conditions (T and τ) has been summarized[89].

$$\Delta H_{r,(T,P)} = \left[\sum \left(\Delta H_{f,(T,P),pi} \cdot q_{pi}\right) - \Delta H_{f,(T,P),fs} \cdot q_{fs}\right]/q_{fs}$$

in which:

- $\Delta H_{r,(T,P)}$ enthalpy of reaction at the actual HTC conditions of T and P [MJ/kg];

- $\Delta H_{f,(T,P),pi}$ enthalpy of formation of the i-th product at T and P;

- q_{pi} amount of the i-th product formed during HTC (expressed in kg for both hydrochar and LPC, and in mol for both water and the gaseous products);

- $\Delta H_{f,(T,P),fs}$ enthalpy of formation of the feedstock at T and P;

- q_{fs} amount of feedstock introduced within the reactor at the beginning of the process (expressed in kg).

To perform the calculation the enthalpies of formation at the actual process conditions have been calculated as:

$$\Delta H_{f,(T,P)} = \Delta H_{f,298}° + dH$$

being $dH = \int_{298}^{T} C_p dT + \int_{1}^{P} V dP$, in which C_p is the heat capacity and V the molar volume.

Solution of the temperature dependence integral

To determine the variations of the heat capacity of the feedstock with temperature, for the actual HTC temperatures, the literature data have been interpolated first linearly and then with a second order polynomial.

Finally, the heat capacity variations with temperature for the feedstock have been obtain as average values between those estimated through both the interpolations.

$$C_{P,feedstock}(T) = -7.30E - 06 \cdot T^2 + 9.92E - 03 \cdot T - 1.00E + 00$$

For both the water and the gaseous products, the integral has been solved using the empirical equation[92]:

$$\int_{T_0}^{T} \frac{C_p}{R} dT = A \cdot T_0 \cdot (t - 1) + \frac{B}{2} \cdot T_0^2 \cdot (t^2 - 1) + \frac{C}{3} \cdot T_0^3 \cdot (t^3 - 1) + \frac{D}{T_0} \cdot \left(\frac{t - 1}{t}\right)$$

where $t = \dfrac{T}{T_0}$.

To assess the heat capacity variations with temperature of 5-HMF, a regression equation has been recovered from data proposed previous research[93], obtained using the Benson group contribution method[90].

A second order polynomial equation has been developed by (Basso, 2016)[94] allowing the integration of $C°_P$ from 298 K to the actual HTC temperatures. Thanks to this polynomial equation necessary data has been obtained.

For the calculation of the heat capacity of phenol, the Joback C_P function from group contributions has been considered (Poling et al., 2007). The property formula is reported below.

$$C_P°(T) = S_0 + S_1 \cdot T + S_2 \cdot T^2 + S_3 \cdot T^3$$

in which:

$$S_0 = \left[\sum_k N_k(CpAk) - 37.93\right]$$

$$S_1 = \left[\sum_k N_k(CpBk) + 0.21\right]$$

$$S_2 = \left[\sum_k N_k(CpCk) - 3.91E - 04\right]$$

$$S_3 = \left[\sum_k N_k(CpDk) + 2.06E - 07\right]$$

and the coefficients $CpAk$, $CpBk$, $CpCk$ and $CpDk$ are reported in previous research[90].

Thus, for the solution of the temperature dependence integral for what concerns phenol, has been integrated from 298 K to the HTC temperature.

Finally, the temperature dependence integral of the LPC has been calculated as a weighted sum of the contributions of both 5-HMF and phenol, according to the assumption have

been made previously.

The heat capacity of the hydrochar has been evaluated through the correlation proposed by Lee (1968), he proposed the following generalized correlation:

$$C_{P,m} = 0.17 + 1.1 \cdot 10^{-4} \cdot T + (3.2 \cdot 10^{-3} + 3.05 \cdot 10^{-6} \cdot T) \cdot VM$$

where

$C_{P,m}$, is the mean heat capacity, expressed in Btu/lb/°F;

T, is the temperature, expressed in °F;

VM, is the volatile matter, expressed in weight percent (dry basis).

RESULTS AND DISCUSSION

The results obtained are presented and discussed in this section.
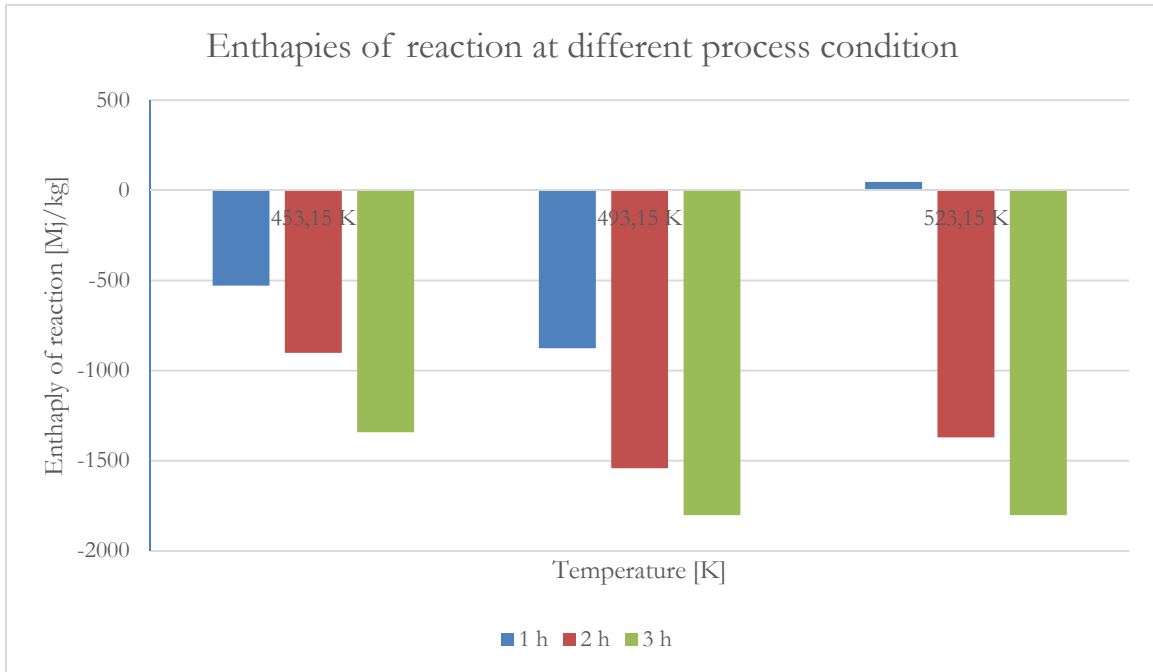
Table 2 Enthalpy of reaction

Table 6 reports the calculated enthalpies of reaction at the different process conditions. On the basis of these results, it can be stated that, under the hypotheses assumed in this work, the HTC process is mostly exothermic therefore a transformation that involves a transfer of

heat from the system to the environment ie, during its development energy is released.

The only difference in result can be seen for the advanced reaction at 523,15 K for 1 hour, in which enthalpy of reaction have a positive value, meaning that the reaction is endothermic.

The calculations made show in particular that enhancing the severity of the process with varying temperatures and residence times, the reaction enthalpies decrease, the more important process variable being the temperature.

These results show abnormal behavior of the model that can be associated with the approximations which are taken into consideration, however further data are needed to validate the model.

HYBRID HTC PLANT ANALYSIS

In the following figure a block scheme of the plant is shown.
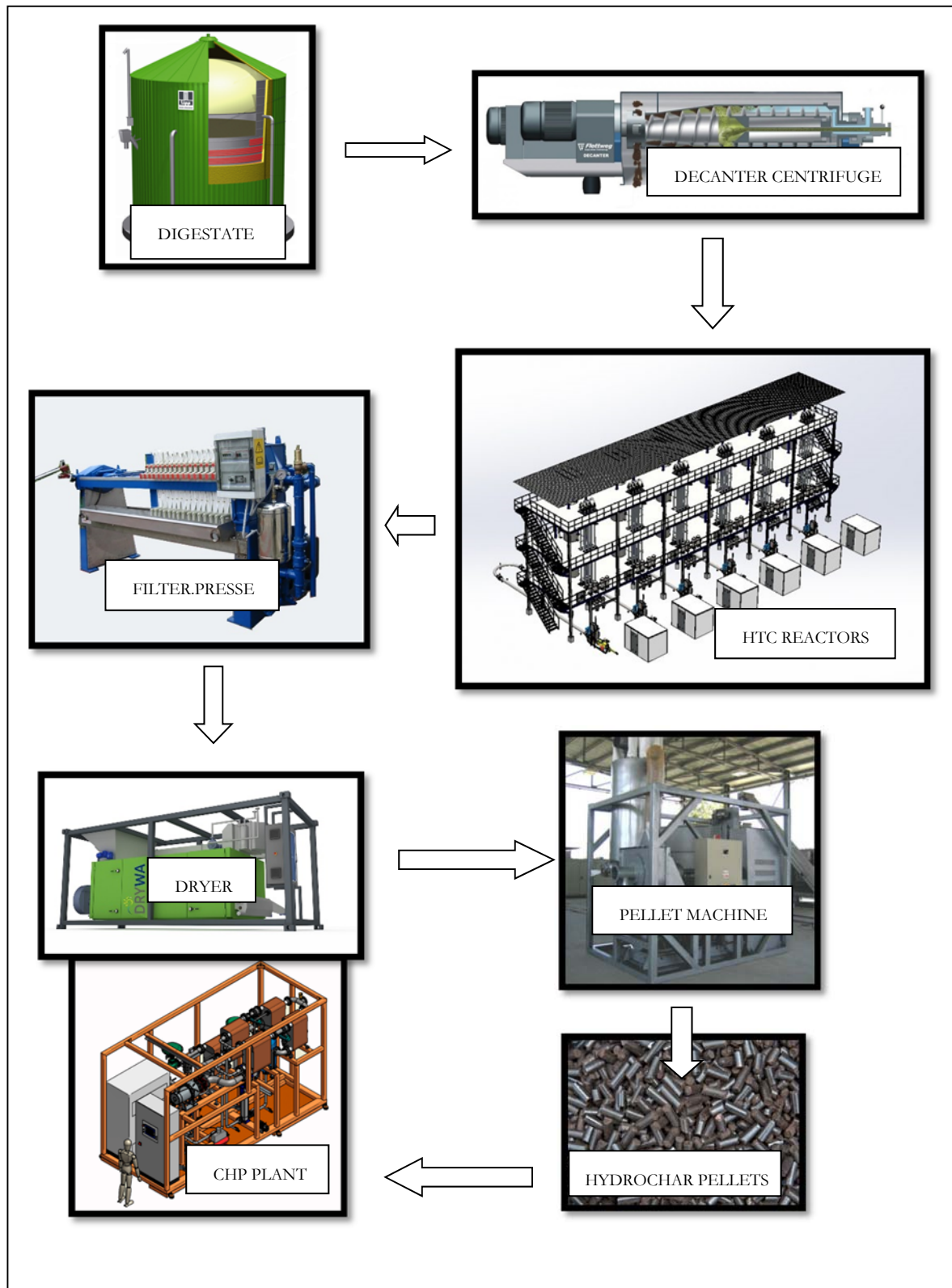
Figure 3 HTC plant scheme

Brief introduction of the process: the design of the plant begins with the arrival of the digestate coming from an anaerobic digestion plant. This material passes throught the centrifugal decanter section, since the digestate before entering the HTC reactors must have a specific moisture characteristics. Once the HTC reactors have been reached, the hydrothermal carbonization reaction takes place which transforms the incoming material into hydrochar and other compounds. In order to exploit the hydrochar, a series of steps are carried out to reduce its moisture content up to 10%. The material will proceed in steps, first in a filter press and then in a dryer. Hydrochar is ready to be pelletized and burned in a cogeneration plant to meet the electrical and thermal energy demands of the plant.

INPUT MATERIAL: DIGESTATE

Digestate is a by-product of the anaerobic digestion process, which is at least as valuable as renewable energy, because of its nutrient and organic matter content.

Using it in agriculture is an efficient way to recycle materials and to decrease the use of mineral fertilizers, indeed returning of organic substances to the soil, which on the one hand means an improvement in growing conditions for the farm and, on the other, dynamic storage of carbon in the soil which in effect is a way of storing carbon dioxide, and reducing its environmental impact. Furthermore, by storing carbon dioxide there's an increase in the soil's drought resilience. This means that the soil has a greater ability to trap water, and even in the event of drought the soil can respond much more to the needs of plants. In Europe the total digestate production in 2010 was 56 Mtonnes per year of which 80–97% was used in agriculture[11]. The digestate agronomic characteristics[95], including organic matter content and quality and plant-available nutrients as well as possibly harmful properties, heavy metals and pathogens, define the effect on soils and plants the agronomic value of the digestate. Anaerobic digestion typically converts most of the feedstock's organic material into biogas while the nutrients of the feedstock are conserved in the digestate in more inorganic and soluble forms. The organic matter in the digestate increases the soil carbon balance that leads to enhanced microbial processes and enzymatic activity, which further increases the long-term nutrient release in soils. In addition, digestate has also been reported to increase germination and plant root growth and soil quality by increasing water balance and soil structure. As a result, the application of the same amount of plant-available nutrients in digestates compared to mineral fertilizers has been found to produce similar and even increased crop yields compared to mineral fertilizers. The amount of digestate applied to land in the EU is defined according to the national legislation which outlines the limits for

nitrogen and phosphorus use per hectare.

This creates a waste disposal problem that needs to be addressed. An interesting alternative to overcome this issue is to carbonize the digestate by means of hydrothermal carbonization, in fact this process takes place in water, so in the case of biomass with high water content, like digestate, water evaporation does not play a significant role in terms of energy balance. Treating digested biomass, as a consequence of anaerobic digestion through the htc process, leads to advantages due to the partial degradation of the biomass.

Organic constituents are then able to hydrothermally decompose, thereby producing a char with a higher C content compared to that of the precursor as well as a more thermally stable structure[96].

In this specific case study, the digestate arrives with a humidity of 91% following an anaerobic digestion process. The material is transported using appropriate tank trucks and deposited in a storage pool, following requirements laid down in the relevant legislation[97]. The storage pool is sized for a storage of material corresponding to the volume accumulated in 90 working days.

Digestate density [kg/m^3]	950
Moisture content digestate [%]	91
Digestate flow rate [m^3/y]	36336

Digestate density was calculated considering humid fraction composed of water and dry matter content with a density of 456 kg/m^3, consist of: 50% humid fraction, 25% pruning and 25% trimmings[98].

Pruning density: 150-200 kg/m^3; Trimmings density: 400-500 kg/m^3; Humid fraction density: 500-700kg/m^3;

- *Dry digestate density:* 50% * 600kg/m^3 + 25% * 175kg/m^3 + 25% * 450kg/m^3 = 456,25 kg/m^3

DECANTER CENTRIFUGE

Digestate from Anaerobic digestion usually contains more than 90% of water, in fact in this specific case study OFMSW treated by digester provides digestate with 91% humidity.

The parameters that influence the products of the HTC processes include the reaction temperature, water ratio and reaction time. As reported in various article[99] temperature and water/biomass ratio had more effect on the densifying the energy content of biomass than reaction time therefore in order to optimize energy densification with a high mass yield, digestate humidity must be brought to an 75% humidity level before entering the reactors where HTC reaction take place.

To do this a decanter centrifuge is needed. In basic terms, decanter comprises a solid cylindrical bowl, rotating at high speed. Inside the bowl is a scroll rotating at a slightly different speed. The differential speed between bowl and scroll provides the conveying motion to collect and remove the solids. A slurry of liquid and suspended solids is fed along the centre line, and is accelerated outwards to join the pond of liquid held on the bowl wall by the centrifugal force. This same force then causes the suspended solids to settle, and accumulate at the bowl wall. The other end of the bowl is sloped inwards, towards the centre, thus providing a beach, up which the solids are conveyed, to be discharged from the bowl, at the top of the beach. Whilst the solids are conveyed up the beach, some of the entrained liquid drains back into the pond, the join the liquid flow towards the far end. The scroll is carried on a hollow axial hub, through which the slurry feed tube passes to the feed zone. The diameter, the number and the pitch of the conveyor flights are chosen to match the needs of the slurry being treated, as are the depth of the pond, the length of the bowl, the conveyor differential speed and the angle of slope of the beach. The basic decanter is completed with a drive motor, usually electrical and a gearbox, which controls the differential speed of the conveyor.

Separated solids are conveyed along the bowl by the scroll to the conical end of the bowl where the solids are discharged by solid outlet. Solids are pressed at the conical section and the dewatering ratio is increased.
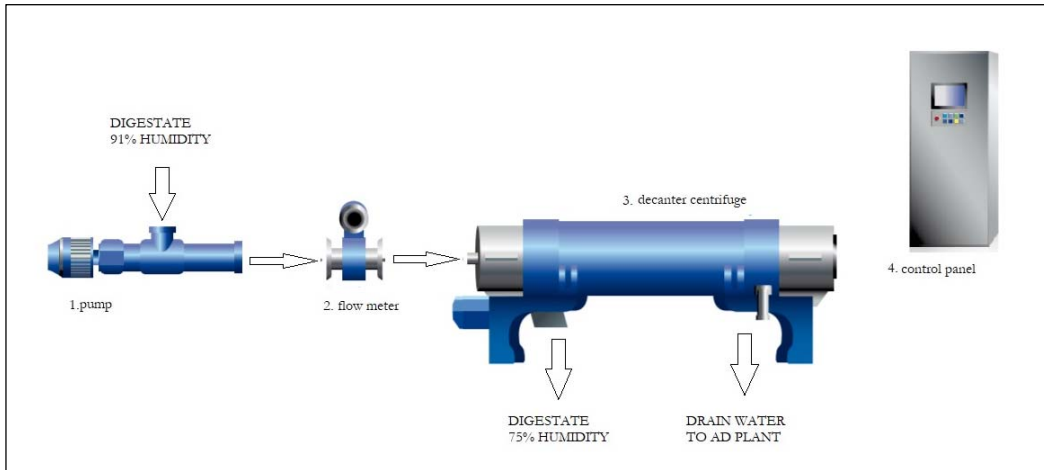
Figure 4 decanter centrifuge scheme
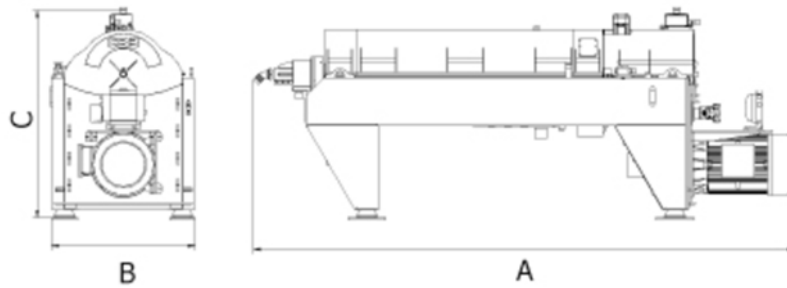
Figure 5 CBB s.r.l. decanter centrifuge product

Decanter type	Trasmission type	Bowl motor [kw]	Max rpm [rpm]	Bowl diameter [mm]	A [mm]	B [mm]	C [mm]	weight [kg]	Hydraulic capacity [m³/h]
CD 30 S	Fixed speed	7.5	5500	290	2350	800	1255	1050	7

Table 3 decanter centrifuge characteristic

Moisture content before centrifuge [%]	91
Moisture content after centrifuge [%]	75
Digestate flow entering the centrifuge [m³/h]	5,05
Digestate flow exiting the centrifuge [m³/h]	2
Loss of water [m³/h]	3,05

Energy consumption of the centrifuge is based on the fact that the time to carry out a cycle of transformation of the material inside the HTC reactors is 3 hours.

Energy consumption (per cycle) [kWh]	22,5

HTC PLANT
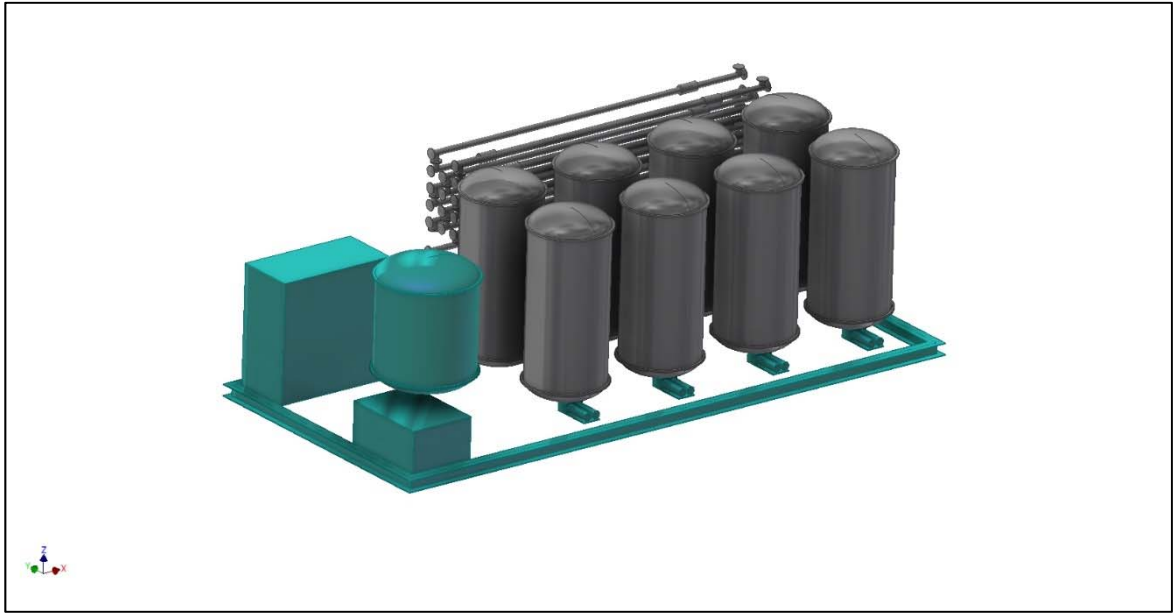
Figure 6 HTC plant scheme
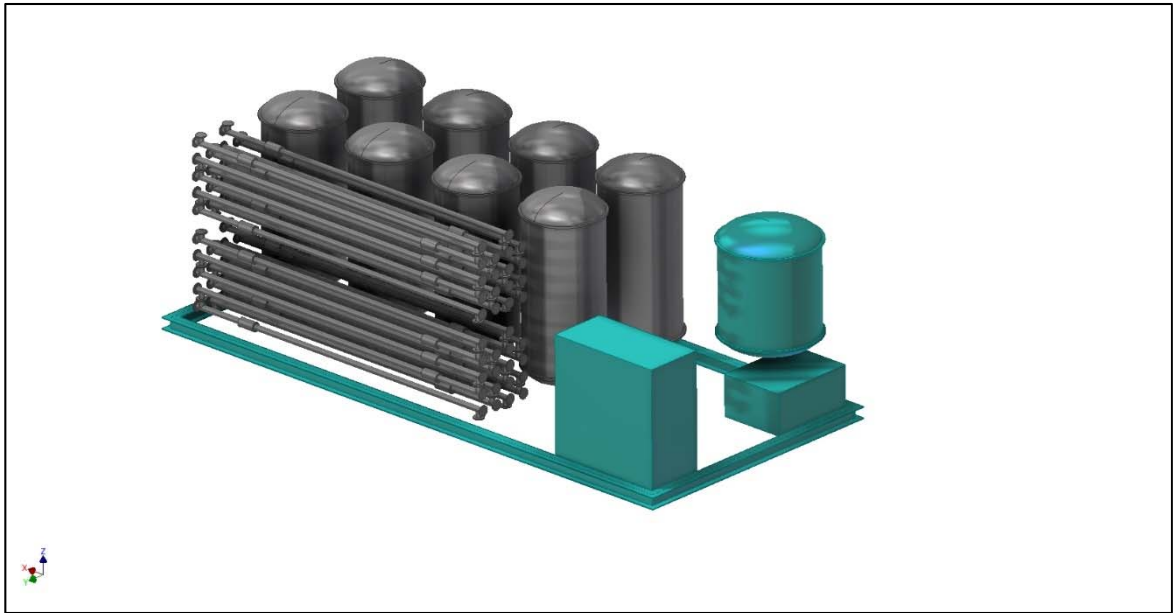
Figure 7 HTC assembly plant

The HTC patented architecture foresees a multiple reactor concept which allows to recover almost entirely the thermal energy and furthermore has a high flexibility and modularity.

This approach provide the process with an almost continuous production rate despite to the strictly discontinuous typical cycle of the traditional HTC batch process.

MAIN CHARACTERISTIC:

- Reaction hypothesis:

  Temperature 220 °C; Working pressure 20 bar; Cycle time 3 hours.

- 6 (or more) reactors with the same capacity (depending on the total number of reactors), in fact, increasing the number of reactors leads to an increase in productivity on equal thermal exchange time, if the capacity of reactors remains the same; alternatively reactors capacity remains the same, but productivity decreases. Each reactor is provided by suitable reactor shaker/mixer

- High efficient upstream heat exchanger (cycle time does not affect the time needed for heat recovery). The heat exchanger phase is carried out maintaining the circuit under pressure (cycle pressure). Heat exchanger is provided continuously by 2 discharge pumps that makes the material flows on both sides thereof.

- Feeding and discharge of material is carried out at atmospheric pressure, isolating each reactor (re-pressurization is made through booster pump in the absence of air, thereby compressing the fluid). Feeding/discharge pumps provide the feeding of the material to reactors and the discharge of treated material.

The functioning of this technology is protected by international patents.

COMPONENT	QUANTITY
Reactor shaker	8
Booster pump	1
Feeding/discharge pump	2
Discharge pump	2
Heat exchanger	1

INPUT HTC MATERIAL

Input material after passing through the anaerobic digester and the centrifuge, arrives at HTC plant. Various scenarios have been taken into account, in order to make best choice in terms of sensitivity analysis, carried out through a series of plant configurations to be able to choose the best in energy and economic and energy terms.

Single reactor capacity [m^3]	2
Number of reactors	8
Number of reactors operating simultaneously	3
Cycle time [h]	3
Operating days per year [d]	300
Operating hours per year [h]	7200

Hourly productivity [m^3/h]	2
Yearly productivity [m^3/y]	14400

- *Hourly productivity:* single reactor capacity * (number of reactors operating simultaneously) / cycle time = 2 m^3 * 3 / 3 h = 2 m^3/h

- *Annual productivity (including water):* operating hours per year * hourly productivity = 7200 h/y * 2 m^3/h = 14400 m^3/y

Digestate density [kg/m^3]	864,1
Digestate flow entering HTC [m^3/y]	14400
Digestate flow entering HTC [ton/y]	12443
Digestate humidity [%]	75

OUTPUT HTC MATERIAL:

Digestate after passing through the centrifuge, reduces the moisture content to 75% and the mass quantity of dry material remain constant. Humidity content doesn't change after HTC reactors. The amount of hydrochar produced per year is considered 25% of total digestate flow.

Hydrochar flow rate [ton/y]	3110
Liquid phase flow rate [ton/y]	9332

- *Hydrochar flow rate:* digestate flow rate * hydrochar percentage = 12443 ton/y * 25% = 3110,75 ton/y

ENERGY BALANCE HTC PLANT:

Energy balance of HTC plant is the result of contributions provided by:

COMPONENT	QUANTITY	WORKING TIME PER CYCLE [h]
Reactor shaker	8	3
Booster pump	1	0,167
Feeding/discharge pump	2	3
Discharge pump	2	3
Heat exchanger	1	3

REACTOR SHAKER:

A general equation from literature[100], provides the necessary tools for sizing and power calculation of the shaker.

From the equation, power is function of these parameters:

a) geometry of the shaker and of the tank (reactor);

b) fluid property (viscosity and density);

c) rotation speed;

d) force of gravity

DATA:

Rotor diameter (D)	[mm]	550
Reactor diameter (T)	[mm]	1200
Density (ϱ)	[kg/m³]	864,1
Rotation speed (N)	[rotation/s]	1
Feeding viscosity ($\mu1$)	[mPa*s]	1
Product viscosity ($\mu2$)	[mPa*s]	0,466

The choice of the rotor diameter was made verifying the following parameter: 0,2< D/T<0,6.

Next step is to calculate Reynolds number with: $= 10^3 \rho\, ND^2/\mu$,

For shaker in feeding reactor $Re1 = 10^3\rho\frac{ND^2}{\mu1} = 261390$ and for shaker in reactor which

treat product change viscosity $Re2 = 10^3\rho\frac{ND^2}{\mu2} = 560923$.
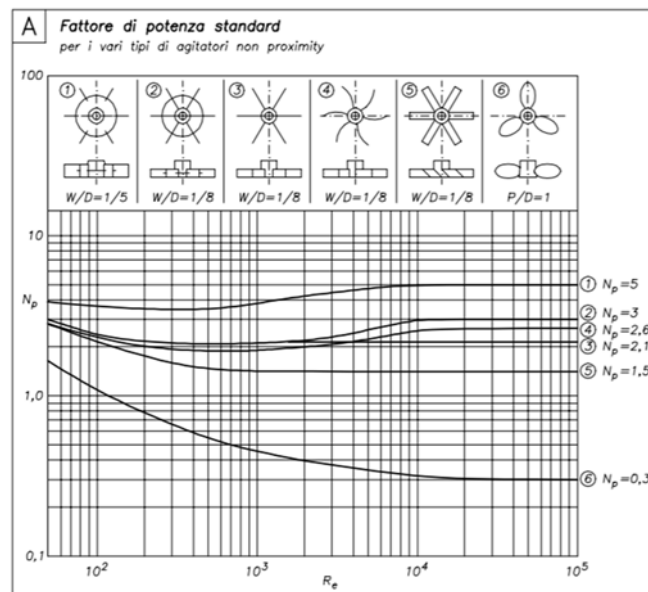
Figure 8 shaker power factor

From figure 9 it is assumed a type 1 form and consequently power factor is: Np= 5

The power is then determined as follows: $P = 10^{-3}\rho\, Np\, N^3 D^5 = 1,74\, Kw$ which is the power for every shaker.

Shakers energy consumption (per cycle) = P * number of shaker * cycle time = 41,76 kWh

Shakers energy consumption (per cycle) [kWh]	41,76

BOOSTER PUMP ENERGY CONSUMPTION:

Booster pump is a screw pump, multistage, with simple mechanical seal.

This pump has the task of bringing the reactor from atmospheric pressure to a working pressure of 20 bar; a contingency extra pressure value of 3 bar has been considered in the calculations in order to account pressure losses during charge phase and contingency on the plant cycle process. The efficiency used for the power pump calculation was found from the characteristic curves of the pumps, thanks to the data sheets from some possible suppliers and thanks to the consulting of HBI srl.

Flow [l/min]	Pressure [bar]	Number of reactors	Number of reactors operating simultaneously	Working time per cycle [h]	η
4	23	8	3	0,167	0,48

$$P = \frac{Q*p}{600} * working\ time\ per\ cycle * number\ of\ reactors\ operating\ simultaneously$$

Booster pump energy consumption (per cycle) [kWh]	0,0768

FEEDING PUMP ENERGY CONSUMPTION (feeding / discharge):

This type of pump is a screw pump, single-stage, with simple mechanical seal and fixed

turns. This type of pump is suitable for the transfer of fluids that contain solid parts in suspension, with a constant flow rate.

Pressure of 2 bar is intended to overcome the pressure losses assumed on the circuit.

Flow [m³/s]	Pressure [bar]	Number of reactors	Number of reactors operating simultaneously	Working time per cycle [h]	η
0,00111	2	8	3	3	0,48

$$P = \frac{Q * p}{\eta} = 0{,}463 \ kW$$

Energy consumption = P * cycle time * number of reactors operating simultaneously

Energy consumption feeding/discharge pump (per cycle) [kWh]	4,2

DISCHARGE PUMP ENERGY CONSUMPTION:

Discharge pump is a screw pump, single-stage, with the same construction features of the feeding pump.

Flow [m³/s]	Pressure [bar]	Number of reactors	Number of reactors operating simultaneously	Working time per cycle [h]	η
0,0005556	5	8	3	3	0,48

$$P = \frac{Q * p}{\eta} = 0{,}579 \ kW$$

Energy consumption = P * cycle time * number of reactors operating simultaneously

Discharge pump energy consumption (per cycle) [kWh]	5,208

HEAT EXCHANGER:

The enthalpy available in the product leaving the reactors, having a temperature of 220 ° C, is partly used to preheat the supply through a heat recovery exchanger.

Thanks to the consulting of Alfa Laval Italy s.r.l. a tubular heat exchanger was chosen.

In the specific case the ViscoLineTM Multitube unit is ideal for the heating, cooling of products with low and medium viscosity that contain fibres and small particulates. The ViscoLine Multitube unit consists of a bundle of tubes mounted inside an outer shell, and welded onto tube plates at both ends. The product medium flows inside these tubes, and the service medium between and around them.

All the product tubes are connected in parallel and the flow is counter-current.

ViscoLine Multitube modules are normally connected in series and mounted on support frame or full frame.
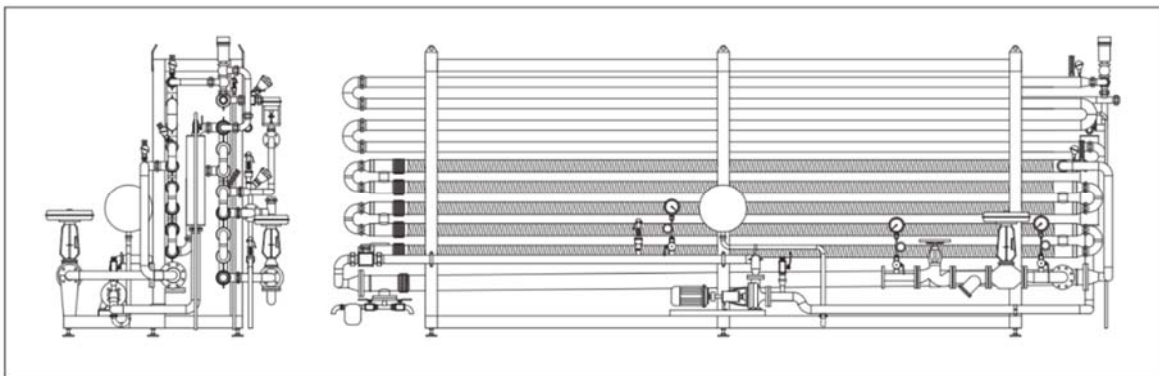
Figure 9 Alfa Laval ViscoLine Multitube system
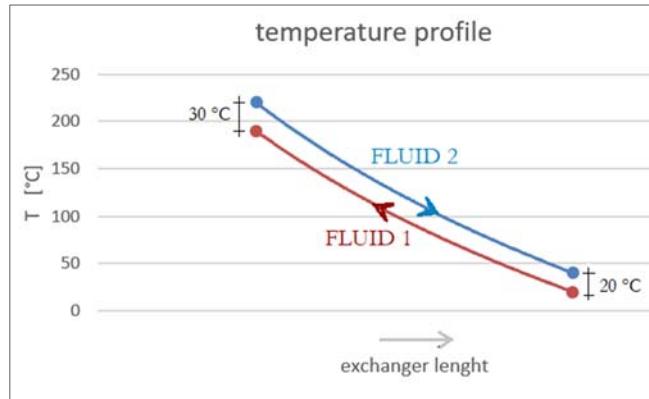
Figure 10 Profile temperature for the heat exchanger

Based upon the exchanger efficiency, the characteristics of the fluid and the flow rate it has been calculated that the fluid 1 obtains a heating after passing into the exchanger from room temperature (20 °C) to 190 °C, while the fluid 2 is cooled by 220 to 40 ° C. The fluid 1 then, thanks to the regenerative exchange, increases its temperature before starting the reaction, which takes place at 220 ° C. A system of electric heaters has been designed to allow the fluid 1 to make a ΔT: 30 °C to reach 220 °C and its energy expenditure is calculated.

The heating of the fluid up to 220 ° C, will be carried out by an electric immersion heater, for each reactor, both in the start-up phase and in the steady state. In order to limit the heat loss and the high temperature protection of the operating personnel, each reactor is lined with insulating material.

Specific gravity [kg/m³]	864,1
Specific heat (water) [J/kg K]	4186
Heat exchanger temperature OUT [°C]	220
Heat exchanger temperature IN [°C]	190

Theoretical heating energy per cycle = single reactor capacity * numbers of reactor operating simultaneously * specific gravity * specific heat * (Heat exchanger temperature OUT - Heat exchanger temperature IN)

- *Theoretical heating energy per cycle* = 2 m³ * 3 * 1000 kg/m³ * 4186 J/(kg K) * (220 – 190) °C
  = 753480 J = 209,3 kWh

Heating energy (per cycle) [kWh]	209,3

BELT PRESS

Belt presses are devices for continuous sludge dehydration, which associate the effect of compression induced by the machine to the action of gravity. The sludge is passed into the space between two rotating belts, one of which, the lower one, has a filtering function, while the upper one exerts a pressure on the mud panel, promoting the separation of the liquid phase which is removed through the lower belt. At the exit of the machine, the separated fraction is detached from the belts by a scrap-cloth and subsequently collected.

The device is provided with an automatic washing system for the sheets, which requires a quantity of water usually equal to the quantity of treated sewage. The solid-liquid separation by means of belt-press leads to the obtainment of a semi solid fraction with a moisture content of 18 to 25%.
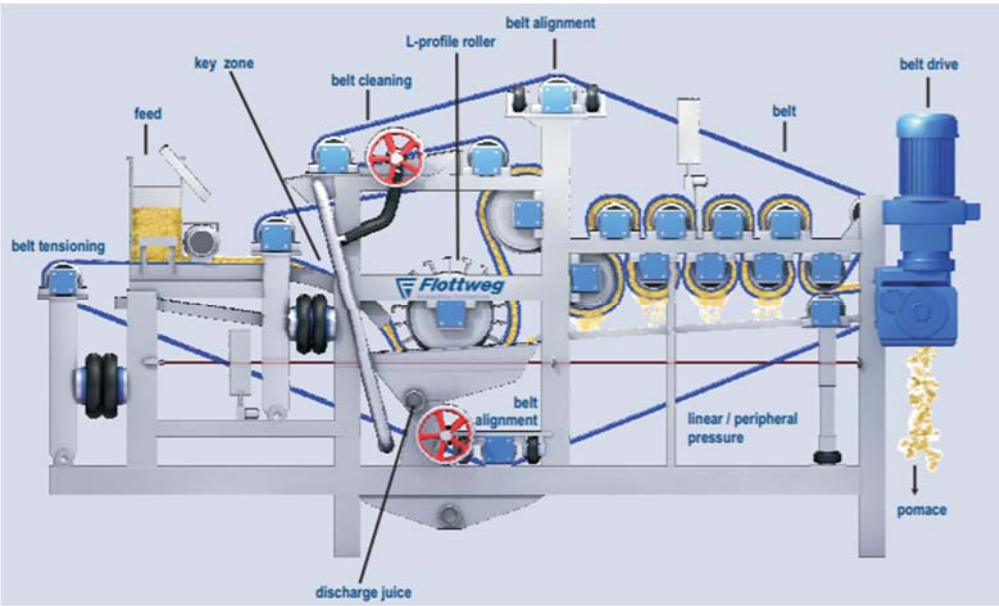
Figure 11 Flottweg belt press functioning
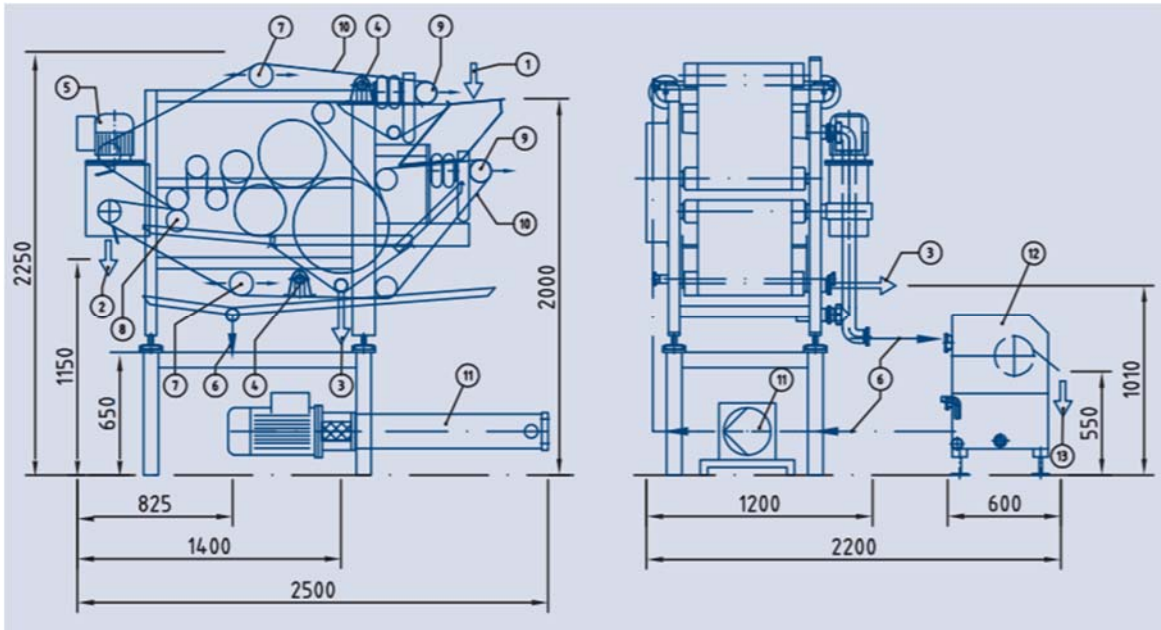
Figure 12 Belt press dimensions

Length [m]	2,50
Width [m]	2,20
Height [m]	2,25
Belt width [m]	0,50
Installed power [kW]	2,2
Weight [kg]	1300
Control air [bar, Nm^3]	6 bar, 4 Nm^3
Max product capacity [kg/h]	500 - 2000

Moisture content before belt press [%]	75
Moisture content after belt press [%]	20
Flow entering the belt press [kg/h]	1728
Flow exiting the belt press [kg/h]	540
Loss of water [kg/h]	1188

Energy consumption (per cycle) [kWh]	6,6

DRYER MACHINE

The drying process reduces the humidity from the solid part of HTC treated material.

For this specific case study a dryer machine from SOLWA s.r.l. was analysed. Thanks to its performances, design, technology and size, it can be placed directly inside the waste water treatment plant without any modification.

This system dries and incinerates sewage sludge, where the input is made of water and hydrochar with a moisture content of about 20% after belt press.
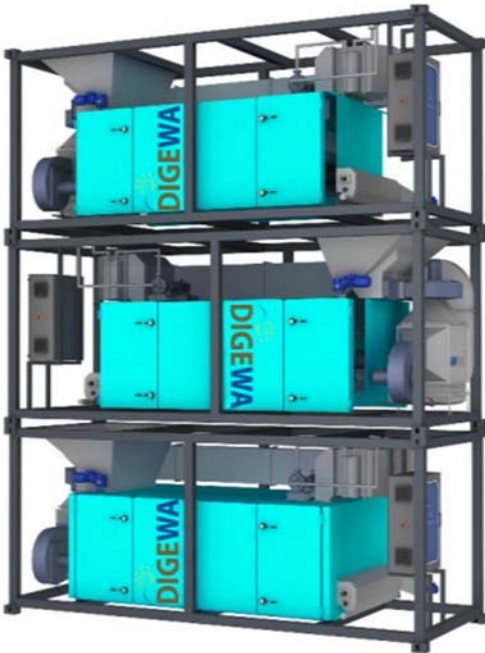
Figure 13 dryer system from SOLWA s.r.l., three stacked modules

INPUT	
Capacity per year [ton/y]	1000
Capacity per hour [kg/h]	119
Initial moisture content [%]	20
OUTPUT	
Final moisture content [%]	10
Water emitted by dryer [kg/h]	71,4

Water emitted by burner [kg/h]	17,85
TECHNICAL CHARACTERISTICS	
Electrical power consumption [kW]	5
Volume air circulation [nm³/h]	3500
Working temperature [°C]	70-95
Size (l * w * h)	6 * 2,5 * 2,5
Maximum stackable modules [n°]	3

Table 4 Solwa data sheet

The material composed by hydrochar and liquid phase which undergoes the dryer machine have the following characteristic:

Moisture content before dryer [%]	20
Moisture content after dryer [%]	10
Flow entering the belt press [kg/h]	540
Flow exiting the belt press [kg/h]	480
Loss of water [kg/h]	60

Assuming to use in series 4 of these dryer machine, after an analysis of energy consumption this result is obtained:

Dryer machine energy consumption per cycle [kWh]	60

PELLET MACHINE

The pelletizing plant is an automatic machine equipped with all the necessary elements to obtain the pellet.

The system consists in enclosing the various mechanisms necessary for the transformation inside a small and ready to use frame in order to avoid a line that develops in length and to avoid problems related to the plant.

The extruder is cylindrical, ideal for high production and for refined products and rarely the die is flat, ideal for products with coarse particle size, for instance soft biomass and ideal for large pellet diameters.

The product to be pelletised must have humidity from 10% to 15%. The quantities may vary according to the hardness and type of the product.

The system consists of the following components:

- Refinery mill

  Intended to grind the product using high strength knives and hardened extruder provided with diameter 5 holes in order to reach a product size of 1- 5 mm, the fine size is important to ensure a maximum quantitative yield by the pelletizer.

- Transportation of refined product

  There is the pneumatic transport of the refined product, from the mill to the dosing hopper, and combined there is the recovery and recycling of the process air in order not to introduce it into the atmosphere.

- Dosing hopper with cyclone

  The dosing hopper is necessary to have always available a quantity of product to be dosed in the right way to the pelletizer.

- Pelletizer

  The pelletizer is made up of a monoblock, equipped with a cylindrical or flat die extruder, 3 compressor rollers, electric motor, reducer, pulleys and belts, inspection doors and automatic greaser.

  The pellet produced varies from a size of 3 mm to a size of 50 mm.

- Translating belt and cup elevator

  The translating belt has the task of moving the hot and friable pellet from the pelletizer outlet to the cup elevator.

  The cup elevator placed next to the pelletizer collects the pellet transferred from the conveyor belt and elevates it to the cooling tower.

- Cooling tower and sieve

  The cooling tower has the task of hosting a certain quantity of product during the

cooling phase. It consists of a pyramidal body to facilitate the descent of the pellets and a sloped sieve placed as a base.

Figure 14 Pellet machine

Length [m]	4
Width [m]	2,5
Height [m]	4
Weight [kg]	3400
Capacity with wood of medium hardness for 6 mm pellets [kg/h]	500
Capacity with soft biomass for pellets 6 mm [kg/h]	1000
Electrical power consumption [kW]	50

The process material which undergoes the pellet machine have the following characteristic:

Material flow rate INPUT [kg/h]	480
Moisture content INPUT material [%]	10

Pellet machine energy consumption per cycle [kWh]	150

TOTAL ENERGY CONSUMPTION ANALYSIS

Decanter centrifuge [kWh]	22,5
HTC plant [kWh]el	51,2
HTC plant [kWh]th	209,3
Belt press [kWh]	6,6
Dryer machine [kWh]	60
Pellet machine [kWh]	150
Total electric energy consumption per cycle	290,3
Total thermic energy consumption per cycle	209,3

COGENERATION

CHP plant (combined heat and power production) means "the set of operations aimed at the combined production of mechanical / electric energy and heat, both considered useful effects, starting from any source of energy. The cogeneration process must achieve a more rational use of primary energy compared to processes that produce the two forms of energy separately. The production of mechanical / electrical energy and heat must take place in a way substantially interconnected in cascade ".

An important application of hydrochar from HTC is direct combustion for heat and power generation. The combustion behavior of hydrochar has been mainly studied at laboratory scale and mostly by means of thermogravimetric analyses (TGA). Also, several authors have successfully investigated co-combustion processes (hydrochar plus coal) as a flexible mechanism to adjust fuel properties (ignition, peak temperature, heat loss, emissions ...) for optimal operation conditions.

From an industrial point of view, the combustion behavior must be observed, paying attention to the operating conditions, and this includes the ash behavior. The ash content in the fuel could lead to several issues in the boiler, fouling, slagging effect, or even ash melting are the most common.

According to (Li et al) who studied the effect of HTC on the combustion of paper sludge,

HTC as a pretreatment improved the combustion slagging and fouling problems, furthermore reduce chlorine content concentration, allowing for the boiler to be operated under better conditions and then providing better combustion yields.

The integration of the HTC technique in a traditional cogeneration power plant (CHP) has been preliminary studied by Saari et al. [62]. They presented a scenario evaluated in terms of the energetic and economic parameters to obtain a profitable project for producing hydrochar with the heat of a combustion plant. The results indicate that the integration of the HTC plant could offer a better economic liability when compared to the stand alone CHP for a district heating.

Hydrochar have also been tested as precursors to produce syn-gas (or, in general, a gas with a calorific value adequate for energetic purposes) by means of gasification processes with air or steam as gasifying agents. Owing to its greater carbon content as compared to the respective precursors, hydrochar can provide a greater proportion of CO and H2 (and under certain circumstances, of CH4). In addition, the gas composition and flow rate is less variable over time, owing to the lower volatile matter of hydrochar.

INPUT CHP MATERIAL :

Figure 15 hydrochar pellet

PCI [MJ/kg]	> 20
Carbon (C)	> 60 %

Hydrogen (H)	> 5,8 - 6,2 %
Nitrogen (N)	> 0,6 – 2,3 %
Sulphur (S)	< 0,3 %
Chlorine (Cl)	< 0,3 %
Melting point of ash in oxidizing atmosphere	> 1200 °C
Grindability (Hardgrove Index ISO 5074-1980)	44 - 52
Volatile	50 – 70 %
Moisture content	10 %
Quantity [ton/y]	3456

Table 5 hydrochar pellet characteristic

Thanks to the consultancy of Uniconfort srl it was possible to have the following data applicable to a typical cogeneration plant based on a Rankine cycle:

Burned power [kW]	3.055
Operating pressure [bar]	12
Gross electric power [kWe]	200
Thermal power to the condenser [kW]	2200

The following figures shows a preliminary high level schematic and a draft general assembly of the plant already produced and that could be taken as a reference for preliminary consideration on the present case.
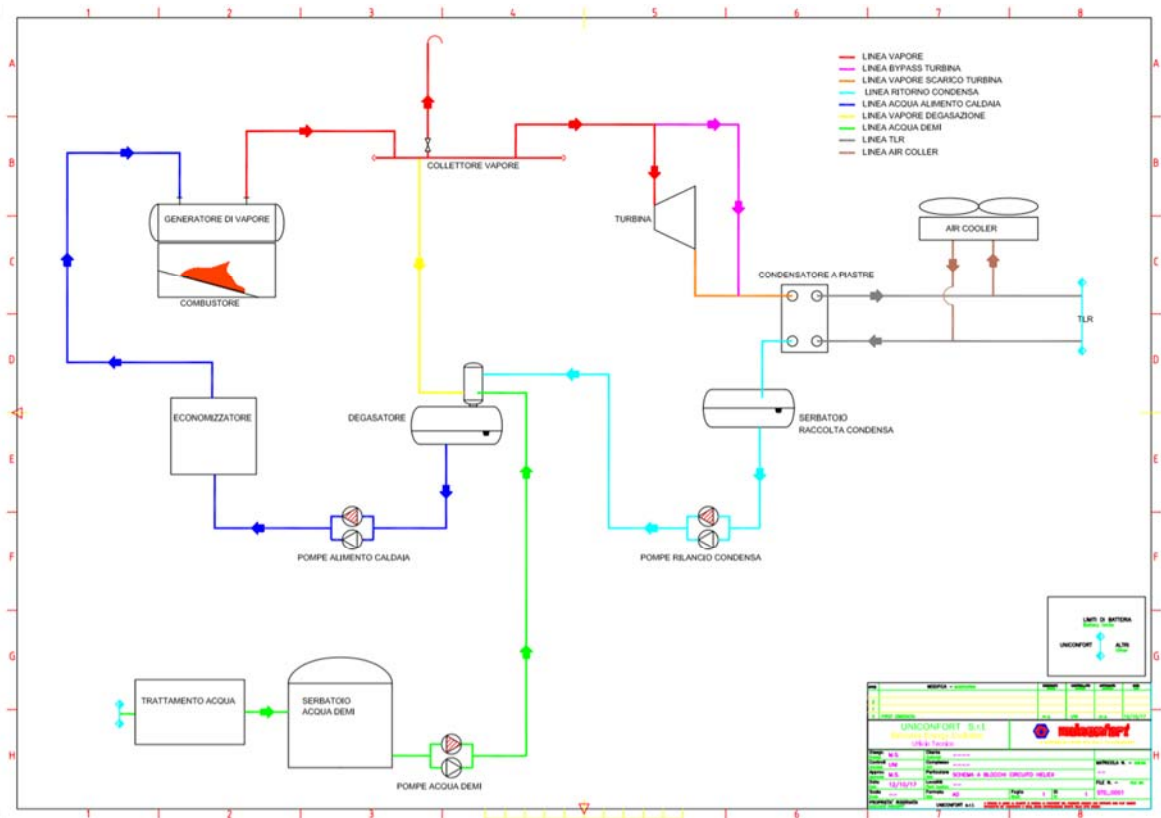
Figure 16 Layout CHP plant
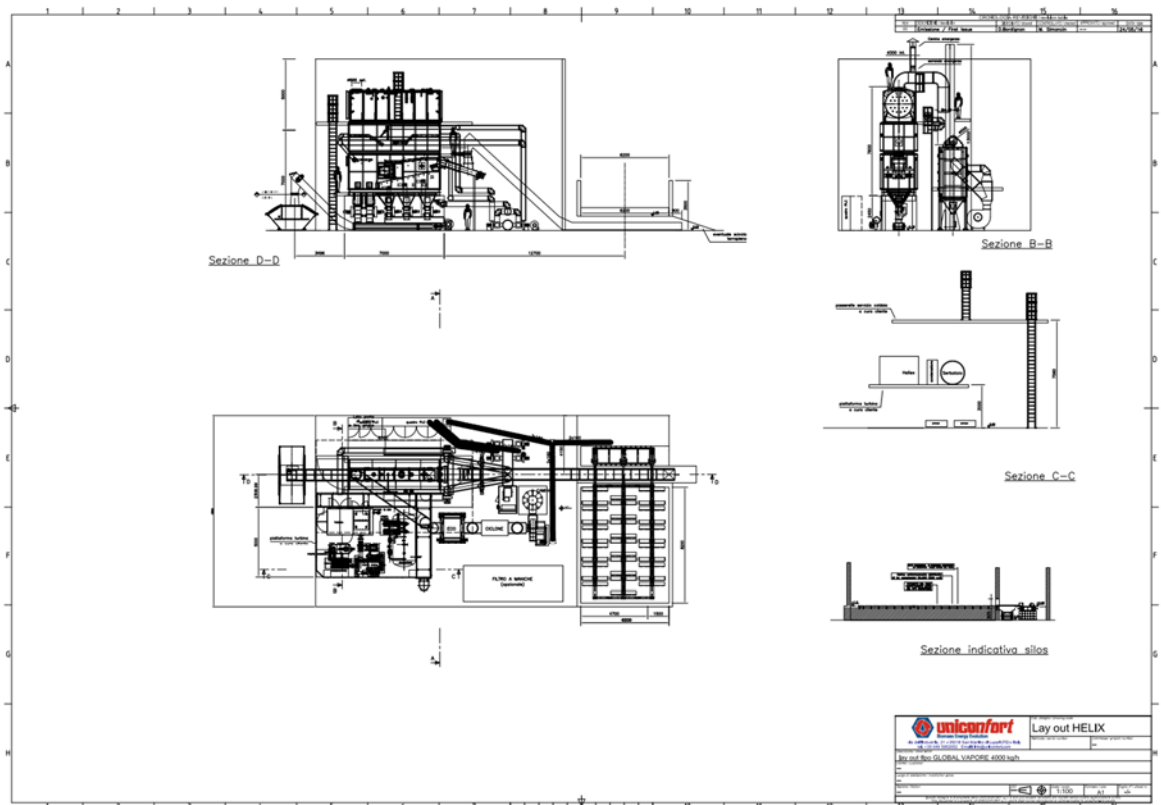
Figure 17 CHP plant section

With information on the CHP cycle powered by hydrochar pellets, the following table shows the production of electrical and thermal energy produced in the cycle time (3 h), using whole hydrochar pellet production.

Total electric energy produced per cycle [kWh$_e$]	600
Total electric energy consumption per cycle [kWh$_e$]	290,3
Total thermic energy produced per cycle [kWh$_{th}$]	6600
Total thermic energy consumption per cycle [kWh$_{th}$]	209,3

It can be seen that the selected CHP plant produces more electric band thermal energy than those required by the digestate enhancement cycle, it will then be analyzed through various scenarios the best way to exploit this system. Furthermore in the following chapter 6.1, 6.2, 6.3 and 6.4 are shown different scenarios in which the pellets produced by the plant are used in various ways. In 6.1 scenario, the hydrochar becomes pellet is totally sold, so a cogeneration plant is not needed; In scenario 6.2, whole produced pellets are burned in the cogeneration plant and electric and thermal energy produced are used in part to satisfy the needs of the plant and the production surplus is sold; In scenario 3 only the quantity necessary to meet the electrical requirements of the plant is burned in the cogeneration plant and the excess hydrochar pellets are sold. As regards the last scenario 6.4, the cogeneration plant is sized to meet the thermal requirement.

PLANT REVIEW
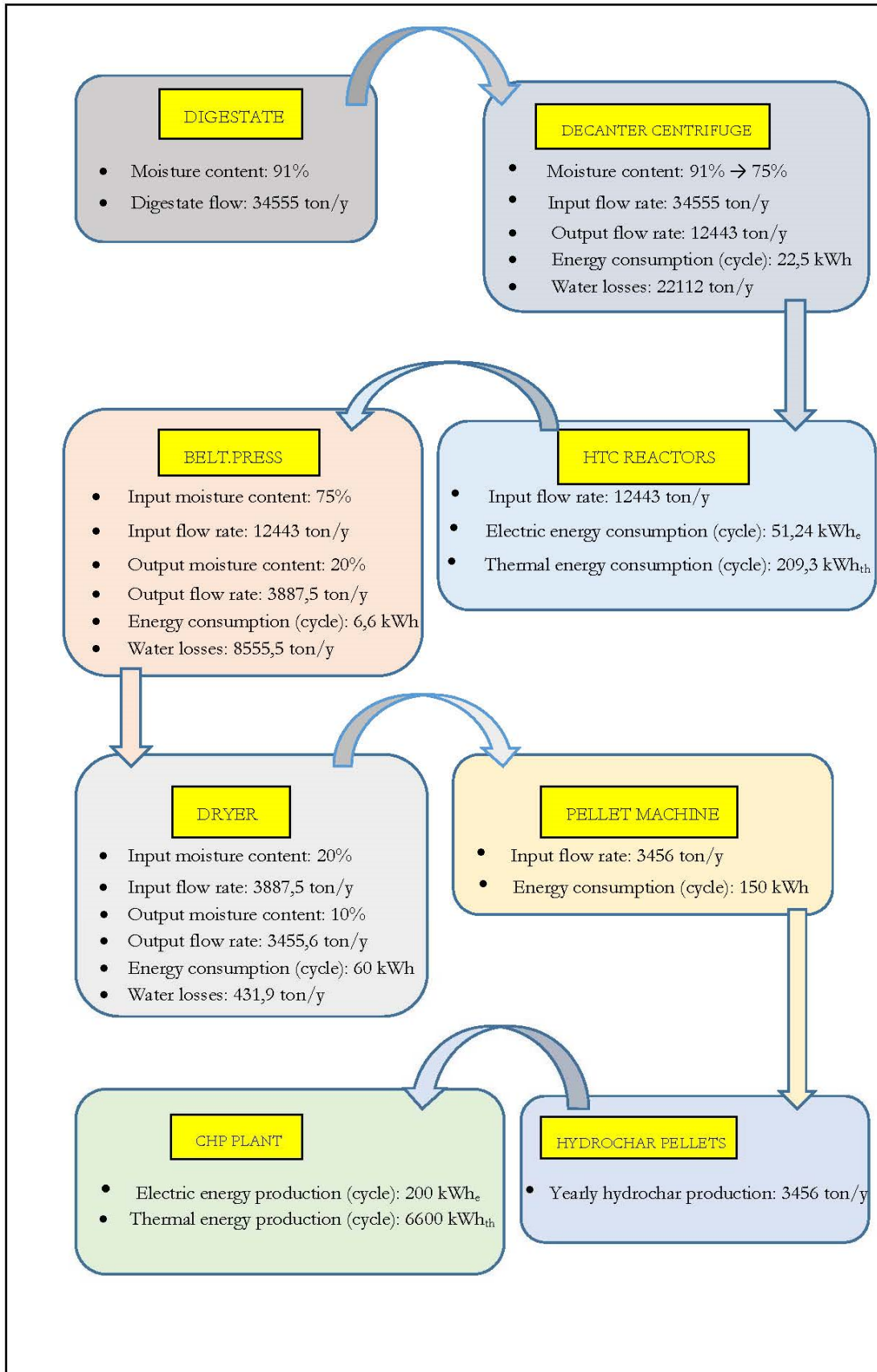
Figure 18 Mass and energy balance of the plant

FINANCIAL ANALYSIS

In the cost / benefit analysis of an energy conversion plant, a widespread economic model is the discounting of the future values of a cash flow, which means the determination of the income and expenses related to the investment made.

The analysis is then carried out considering an initial instant, coinciding with the start of the plant operation and a useful plant life of "n" years. To carry out the feasibility study it is not necessary that the duration of the investment is equal to the useful life of the plant, generally it is considered a shorter time, to prevent any unexpected events such as technological obsolescence. Thanks to some important economic index, it's possible to evaluate the suitability of an investment, including: the net present value (VAN), the recovery time (TR) and profit index (IP). The net present value measures the discounted economic surplus of the net benefits, compared to the initial investment; therefore the discounting is referred to the year zero, which is set as the beginning of the cash flow.

The discount rate that is appropriately chosen according to the characteristics of the project plays an important role.

At this point, it's possible to define the net present value as the discounted difference at any instant of the outlays and revenues, and assuming that the initial investment is concentrated at year zero, ie:

$$VAN = -I_0 + \sum_{j=1}^{n} D_j * (1 + a)^j$$

Where:

- I_0 : initial investment;

- C_j : total operating costs at j-th year. Includes energy source supplying costs and ordinary maintenance costs;

- R_j : total operating revenue at j-th year. Includes revenues for the disposal of digestate and the sale of energy produced or the sale of hydrochar;

- $D_j = R_j - C_j$ availability or net income or gross profit generated by the project in the year j-th

- a : discount rate

The investment is convenient if the VAN is positive. When comparing different investments, the one characterized by the higher ratio of VAN / I_0 will be chosen. Another very useful criterion in the analysis of investments is the recovery time (TR), defined as the time required for the availability of cash to generate exactly the net investment that made it possible, ie it represents the number "n" of years in which the VAN is zero:

$$0 = -I_0 + \sum_{j=1}^{n} D_j * (1 + a)^j$$

SCENARIO 1:

In the first scenario is analysed the upgrading of digestate flow trought HTC plant using 8 reactors and selling the whole hydrochar pellets production. For this scenario the cogeneration plant with the relative costs is not considered.

Single reactor capacity [m^3]	2
Number of reactors	8
Number of reactors operating simultaneously	3
Cycle time [h]	3
Operating hours per year [h]	7200
Digestate flow rate HTC plant [m^3/y]	14400

COST ESTIMATION WITH ANALYTICAL METHODS: SIMULATIONS

This chapter presents the results of the simulations developed with the analytical method in order to determine, on the basis of a detailed assessment of the main cost and revenue items.

Since there is no market developed for this type of system that allows us to make comparisons, various assumptions have been made in order to obtain a result that may be the closest to the real case.

To this end, it must contain the industrial cost organised to take account of:

- Costs related to investment expenditure for the construction of the plant;

- Maintenance costs (maintenance people, both for annual extraordinary maintenance and ordinary maintenance);

- Cost of maintenance (spare parts, consumables, various maintenance equipment, maintenance services, etc.);

- Electricity costs necessary for the operation of the plant.

Revenues were considered:

- from the incoming digestate stream minus the costs of disposing of the contaminated water after the centrifugal decanter

- evaluating the sale of the hydrochar pellets, considering the selling price equal to that of a usual wood pellet EN Plus A1, given that there is no market for hydrochar pellets;

- considering the revenues from the sale of electricity produced by the cogeneration plant;

- as regards thermal energy, the best way to enhance it is still being evaluated.

COSTS RELATED TO INVESTMENT EXPENDINDITURE OF THE PLANT

Price of the HTC plant includes design, management, materials, construction and assembly.

Components considered in the analysis of the investment expenditures of the plant are listed in the following table:

Heat exchanger	Air compressor
Reactors	Sensors (temperature, pressure, reactor's level)
Reactors mixer	Safety valves (PED)
Main frame	Control system (boards, electronic components, etc.)
Motorization for reactor mixers	Electric cabinet (assembled)
Volumetric pump (feeding/discharge pump)	Electric plant
Volumetric pump (reactors' discharge)	Human-Machine Interface

Mixing feeder	Heaters
Plumbing and accessories (valves, other components)	Discharge/feeding tank
Boost pump	Automatic discharge system and screw conveyor

Table 6 List of HTC plant components

- Costs for Decanter centrifuge includes the electrical board and the on-site assembly of the machine.

- Costs for Belt press includes: Consultancy regarding the separation technology; Process development and optimization; Design, planning and construction of complete process lines; Installation and commissioning.

- Costs for Dryer machine includes: Product development consultancy; on-site assembly and after-sales assistance.

- Costs for Pellet machine includes: various machine components such as Refinery mill; Transportation of refined product; Dosing hopper with cyclone; Pelletizer; Trasportating belt and cup elevator; Cooling tower and sieve. Futhermore includes on-site assembly and after-sales assistance.

Decanter centrifuge [€]	95000
HTC plant [€]	2450000
Belt press [€]	64000
Dryer machine [€]	46000
Pellet machine [€]	58000
Total plant price [€]	2713000

For the evaluation of the total price of the plant, preliminary estimates of various companies and internal HBI srl company evaluations were used.

MAINTENANCE COSTS

Maintenance costs includes: Maintenance personnel, both for annual extraordinary maintenance and ordinary maintenance intending for ordinary maintenance, the interventions necessary to integrate or maintain the efficiency of existing technological systems.

For extraordinary maintenance, on the other hand, we mean the works and modifications necessary to renew parts of the plants through replacement.

It's considered to use personnel during the period of downtime, therefore approximately for 60 days. The cost of personnel is evaluated considering the employment of 2/3 people, 12 hours a day of work, with a pay of 30 €/h.

For Decanter centrifuge, Belt press, Dryer machine and Pellet machine it's assumed that the maintenance costs correspond to 10% of the cost of machinery.

Decanter centrifuge [€]	9500
HTC plant [€]	55000
Belt press [€]	6400
Dryer machine [€]	4600
Pellet machine [€]	5800
Maintenance costs per year [€]	81300

Various assumptions have been made regarding cost of maintenance such as spare parts, consumables, various maintenance equipment and maintenance services.

Maintenance costs per year [€]	75000
TOTAL maintenance costs per year [€]	156300

MANPOWER COSTS OF THE PLANT

As regards manpower costs use of skilled labour, assigned to work management and 24h surveillance of the plant, is considered.

Manpower cost [€/h]	24
Manpower costs per year [€]	172800

ENERGY CONSUMPTION COSTS

Electricity prices for industrial consumers are defined as follows: Average national price in Euro per kWh without taxes applicable for the first semester of each year for medium size industrial consumers (Consumption Band Ic with annual consumption between 500 and 2000 MWh). Until 2007 the prices are referring to the status on 1st January of each year for medium size consumers (Standard Consumer Ie with annual consumption of 2000 MWh).

POLAND	2009	2010	2011	2012	2013	2014	2015	2016	2017
	0,0857	0,0929	0,0929	0,0869	0,0883	0,0777	0,0833	0,0762	0,0786

Table 7 EUROSTAT 2017 - energy costs EUR per kWh
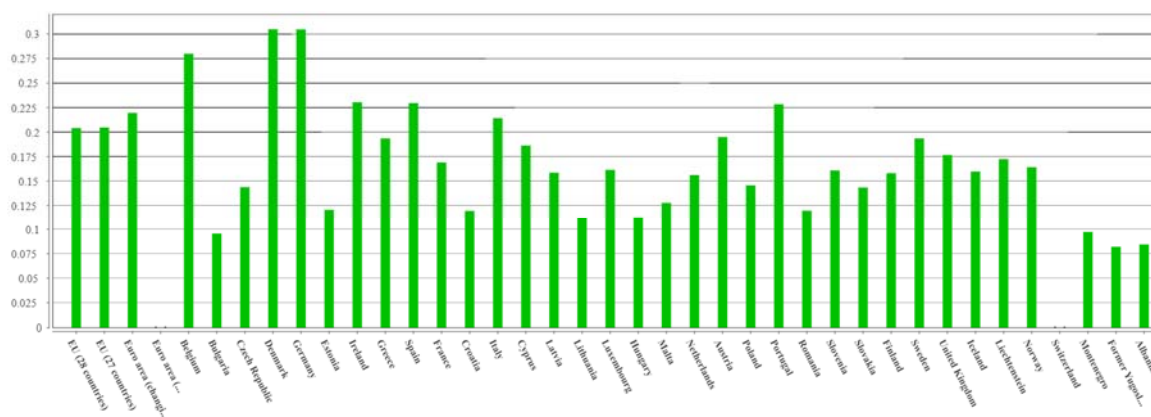
Figure 19 European energy costs EUR per kWh - Eurostat 2017

Average energy costs [€/kWh]	0,0786
Total electric energy requirements (per cycle) [kWh]	290,3
Cycle cost for energy [€]	22,8
Daily cost of energy [€]	182,4
Yearly cost of energy [€]	54720

- *Total electric energy requirements (per cycle):* decanter centrifuge + HTC plant + belt press + dryer machine + pellet machine = 22,5 kWh + 51,2 kWh + 6,6 kWh + 60 kWh + 150 kWh = 290,3 kWh

- *Cycle cost for energy:* Total energy requirements (per cycle) * energy cost= 290,3 kWh * 0,0786 €/kWh = 22,8 €

- *Daily cost for energy:* number of cycle per day * cycle cost for energy = 24/3 * 22,8 € = 182,4 €/d

- *Yearly cost for energy:* operating days per year * daily cost for energy = 300 * 182,4 € = 54720 €/y

Total heating energy consumption (per cycle) [kWh]	209,3
Heating energy cost (per year) [€]	39482

Thermal energy considered includes the energy to enhance the material inside the reactor from 190 to 220 ° C before the reaction takes place. For this temperature rise, heaters are used as shown in the chapter 5.3.5. It's considered that the thermal energy is provided by electric heaters with 100% efficiency, it imputes the cost equal to that of the electrical energy.

VAN, TR AND IP OF TOTAL PLANT

Yearly quantity to be disposed of [ton/y]	12443
Material disposal cost [€/kg]	0,07
Yearly revenue disposal of incoming material [€]	871010
Yearly revenue hydrochar sale [€]	518340
Estimated yearly revenue [€]	1389350

In order to calculate the revenue from the disposal incoming material, the input flow rate to the reactors of the HTC plant is taken into consideration, since it is considered that from the centrifugal decanter all the contaminated water at the output must be disposed of at the same cost as the incoming digestate.

- *Yearly revenue disposal of incoming material:* 12443 ton/y * 0,07 €/kg = 871010 €

- *Yearly revenue hydrochar sale:* 3455,6 ton/y * 0,15 €/kg = 518340 €

- *Estimated yearly revenue:* 871010 € + 518340 € = 1389350 €

Decanter centrifuge [€]	95000
HTC plant [€]	2450000
Belt press [€]	64000
Dryer machine [€]	46000
Pellet machine [€]	58000
Total plant price [€]	2713000

Years of investment [y]	10
Real discount rate [r]	r = 0,085
Rate of increase of the general price index [f]	f = 0,015
Rate of increase of the energy price index [%]	0
Notional discount rate (cost of capital at current prices) [R]	R = 0,1
Real discount rate [i]	i = 0,1

- *Estimated yearly expenditure, with manpower:* Yearly cost for energy and heating + Yearly maintenance cost + yearly manpower cost = 94922 + 156300 + 172800 = 424022 €

Estimated yearly expenditure with manpower [€]	424022

- *discount factor:* $1 / (1 + \text{real discount rate})^{\text{year}}$

- *yearly discounted cash flow:* (yearly estimated profit – yearly estimated expenditure) * discount factor

- *Total discounted cash flow:* sum of annual cash flows up to the considered year

- *VAN:* sum of discounted cash flow - investment

- *Recovery time:* investment expenditure / ((total cash flow discounted to the year 10) / number of investment years)

- *Profit index:* (VAN + investment expenditure) / investment expenditure

Year	Discount factor	Yearly discounted cash flow	Total discounted cash flow
1	0,909090909	878238,0218	878238,0218
2	0,826446281	798398,2017	1676636,223
3	0,751314801	725816,547	2402452,77
4	0,683013455	659833,2245	3062285,995
5	0,620921323	599848,3859	3662134,381
6	0,56447393	545316,7145	4207451,095
7	0,513158118	495742,4677	4703193,563
8	0,46650738	450674,9706	5153868,534
9	0,424097618	409704,5188	5563573,052
10	0,385543289	372458,6534	5936031,706
Net present value	VAN = 3223032 €		
Recovery time	TR = 4,6 years		
Profit index	IP = 2,19		

Table 8 VAN, TR and IP of the plant scenario 1

SCENARIO 2

In this second scenario, CHP plant is added to the configuration. Thanks to this system electric and thermal energy derived from the combustion of whole amount of hydrochar pellets, is partly used to satisfy the electrical and thermal consumption of the plant and partly sold to the grid.

In this case the costs of the CHP plant will be added and in the revenue / costs analysis there will be not earnings from the sale of the hydrochar pellets, but there will be no budget expenditure in terms of electricity and thermal expenditure. There will also profits from the sale of electricity to the grid as the CHP plant produces more energy than necessary.

Amount of burnt hydrochar pellets [ton/y]	3456
Total electric energy produced per cycle [kWh]	600
Total electric energy consumption per cycle [kWh]	290,3
Total thermic energy produced per cycle [kWh]	6600
Total thermic energy consumption per cycle [kWh]	209,3

Considering resale price 5 c€ / kWh, profit from electricity sales:

Annual profit from energy sales [€]	37164

Investment expenditures unlike scenario 1 are subject to an increase due to the price of the cogeneration plant:

Decanter centrifuge [€]	95000
HTC plant [€]	2450000
Belt press [€]	64000
Dryer machine [€]	46000
Pellet machine [€]	58000
CHP plant [€]	800000
Total plant price [€]	3513000

The revenues, unlike scenario 1, will be made up of the energy produced by the cogeneration plant, minus the one needed for the operation of the plant:

Yearly quantity to be disposed of [ton/y]	12443
Material disposal cost [€/kg]	0,07
Yearly revenue disposal of incoming material [€]	871010
Yearly profit for energy sale [€]	37164
Estimated yearly revenue [€]	908174

Estimated yearly expenditure with manpower for this scenario doesn't consider the costs for electricity and heating, however, maintenance costs are increased by 10% of the CHP plant value:

Estimated yearly expenditure with manpower [€]	409100

- *Estimated yearly expenditure with manpower:* Yearly maintenance cost + yearly manpower cost = 156300 + 80000 + 172800 = 409100 €

Year	Discount factor	Yearly discounted cash flow	Total discounted cash flow
1	0,909090909	453703,4327	453703,4327
2	0,826446281	412457,6661	866161,0988
3	0,751314801	374961,5147	1241122,613
4	0,683013455	340874,1042	1581996,718
5	0,620921323	309885,5493	1891882,267
6	0,56447393	281714,1357	2173596,403
7	0,513158118	256103,7598	2429700,162
8	0,46650738	232821,5998	2662521,762
9	0,424097618	211655,9998	2874177,762
10	0,385543289	192414,5453	3066592,307
Net present value	VAN = -446408 €		
Recovery time	TR = 11,5 years		
Profit index	0,87		

Table 9 VAN, TR and IP of the plant scenario 2

SCENARIO 3

In this scenario it's considered that the CHP plant burns pellets in such quantity as to supply the electrical energy necessary for the plant and that the remaining hydrochar pellets are sold.

It's assumed to burn approximately half of the annual quantity produced, so that the CHP system will produce about half the electrical power for which it was sized.

In this way there will be no electrical expenses for the operation of the plant and the hydrochar pellets can be sold.

Energy production from cogeneration plant:

Amount of burnt hydrochar pellets [ton/y]	1728
Total electric energy produced per cycle [kWh]	300
Total electric energy consumption per cycle [kWh]	290,3
Total thermic energy produced per cycle [kWh]	3300
Total thermic energy consumption per cycle [kWh]	209,3

Investment expenditures are the same than scenario 2:

Decanter centrifuge [€]	95000
HTC plant [€]	2450000
Belt press [€]	64000
Dryer machine [€]	46000
Pellet machine [€]	58000
CHP plant [€]	800000
Total plant price [€]	3513000

The revenues in this scenario come from: incoming material that would be material that would otherwise have to be disposed of; from the sale of the hydrochar pellets.

Yearly quantity to be disposed of [ton/y]	12443
Material disposal cost [€/kg]	0,07
Yearly revenue disposal of incoming material [€]	871010
Yearly revenue from hydrochar pellet sale [€]	259200
Estimated yearly revenue [€]	1130210

Estimated yearly expenditure with manpower for this scenario doesn't consider the costs for electricity and heating and maintenance costs are increased by 10% of the CHP plant value compared to scenario 1:

Estimated yearly expenditure with manpower [€]	409100

Year	Discount factor	Yearly discounted cash flow	Total discounted cash flow
1	0,909090909	655527,0691	655527,0691
2	0,826446281	595933,6992	1251460,768
3	0,751314801	541757,9083	1793218,677
4	0,683013455	492507,1894	2285725,866
5	0,620921323	447733,8085	2733459,675
6	0,56447393	407030,735	3140490,41
7	0,513158118	370027,9409	3510518,351
8	0,46650738	336389,0372	3846907,388
9	0,424097618	305808,2157	4152715,603
10	0,385543289	278007,4688	4430723,072
Net present value	VAN = 917723 €		
Recovery time	TR = 7,9 years		
Profit index	IP = 1,26		

Table 10 VAN, TR and IP of the plant scenario 3

SCENARIO 4

Designing the cogeneration plant to meet the thermal energy demands of the plant, a series of assumptions were made. Considering the Uniconfort consultancy that has sized the system to burn the entire quantity of hydrochar pellets produced in the boiler, we have a thermal energy production of 6600 kWh$_{th}$, while the thermal energy consumption of the plant is about 210 kWh$_{th}$ per cycle, it is therefore considered to scale the plant 30 times by a proportion, in this way there will be a production of thermal energy that corresponds to the required one. The consumption of pellets will be much lower, so there will be revenues due to the sale of the hydrochar pellets as well as a lower cost of the cogeneration plant.

Amount of burnt hydrochar pellets [ton/y]	110
Total electric energy produced per cycle [kWh]	19
Total electric energy consumption per cycle [kWh]	290,3
Total thermic energy produced per cycle [kWh]	210
Total thermic energy consumption per cycle [kWh]	209,3

Investment expenditures in scenario 4:

Decanter centrifuge [€]	95000
HTC plant [€]	2450000
Belt press [€]	64000
Dryer machine [€]	46000
Pellet machine [€]	58000
CHP plant [€]	100000
Total plant price [€]	2813000

The revenues in this scenario come from: incoming material that would be material that would otherwise have to be disposed of; from the sale of the hydrochar pellets.

Yearly quantity to be disposed of [ton/y]	12443
Material disposal cost [€/kg]	0,07
Yearly revenue disposal of incoming material [€]	871010
Yearly amount of hydrochar pellet on sale [€]	3346
Yearly revenue from hydrochar pellet sale [€]	501900
Estimated yearly revenue [€]	1372910

The expenditure in scenario 4 are given by the maintenance costs increased by 10% of the value of the cogeneration plant compared to scenario 1, by manpower costs and by electricity costs as the CHP system satisfies the electricity demand only in a small part.

- *Estimated yearly expenditure, with manpower:* Yearly cost for energy + Yearly maintenance cost + yearly manpower cost = 51178 + 166300 + 172800 = 390278 €

Total electric energy requirements (per cycle) [kWh]	271,3
Yearly cost of energy [€]	51178
Estimated yearly expenditure with manpower [€]	390278

Year	Discount factor	Yearly discounted cash flow	Total discounted cash flow
1	0,909090909	893301,5855	893301,5855
2	0,826446281	812092,3504	1705393,936
3	0,751314801	738265,7731	2443659,709
4	0,683013455	671150,7028	3114810,412
5	0,620921323	610137,0026	3724947,414
6	0,56447393	554670,0023	4279617,417
7	0,513158118	504245,4567	4783862,873
8	0,46650738	458404,9606	5242267,834
9	0,424097618	416731,7824	5658999,616
10	0,385543289	378847,0749	6037846,691
Net present value	VAN = 3224847 €		
Recovery time	TR = 4,7 years		
Profit index	IP = 2,15		

Table 11 VAN, TR and IP of the plant scenario 4

SENSITIVITY ANALYSIS

A sensitivity analysis was also performed for scenario 1 in order to verify the modularity of HTC technology, which is one of its characteristics.

	Number of reactors	6	7	8	9	10	11	12	
Costs	Investment expenditure	2.034.810	2.373.945	2.713.000	3.052.215	3.391.350	3.730.485	4.069.620	€
	Maintenance costs	124.500	140.867	156.300	173.600	189.967	206.333	222.700	€/year
	Manpower costs	172.800	172.800	172.800	172.800	172.800	172.800	172.800	€/year
	Energy costs	64.744	79.461	94.922	108.896	123.613	138.330	153.047	€/year
Revenue	Disposal of incoming digestate	290.304	580.608	871.010	1.161.216	1.451.520	1.741.824	2.032.128	€/year
	Hydrochar sale	172.800	345.600	518.340	691.200	864.000	1.036.800	1.209.600	€/year
	VAN	-1.413.842	901.600	3.223.032	5.532.485	7.847.928	10.163.370	12.478.813	€
	TR	32,77	7,25	4,60	3,56	3,02	2,68	2,46	Year
	IP	0,31	1,38	2,19	2,81	3,31	3,72	4,07	

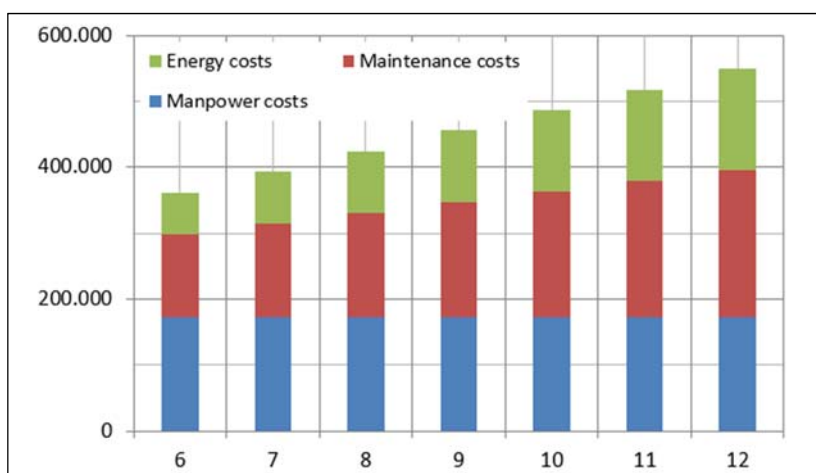**Table 12 Sensitivity analysis of scenario 1**

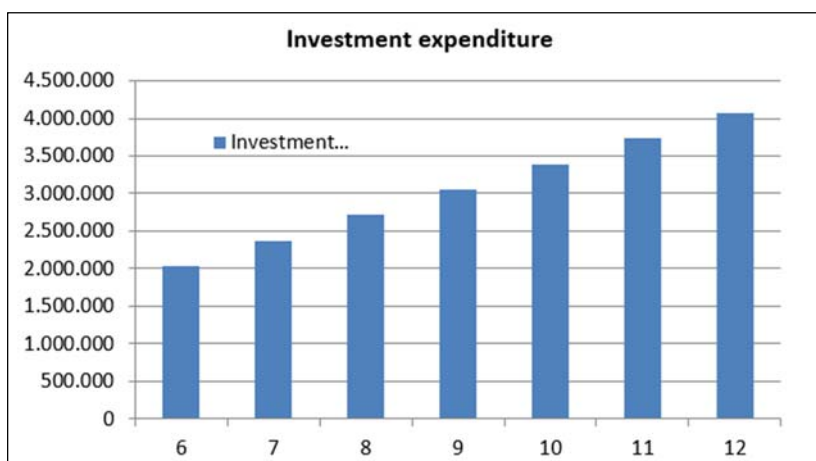**Figure 20 Costs of energy, manpower and maintenance for sensibility analysis of scenario 1**

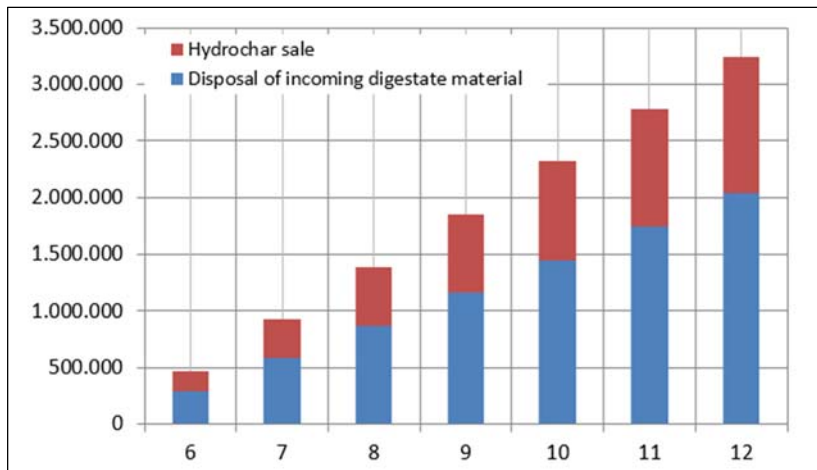**Figure 21 Investment expenditure for sensibility analysis of scenario 1**

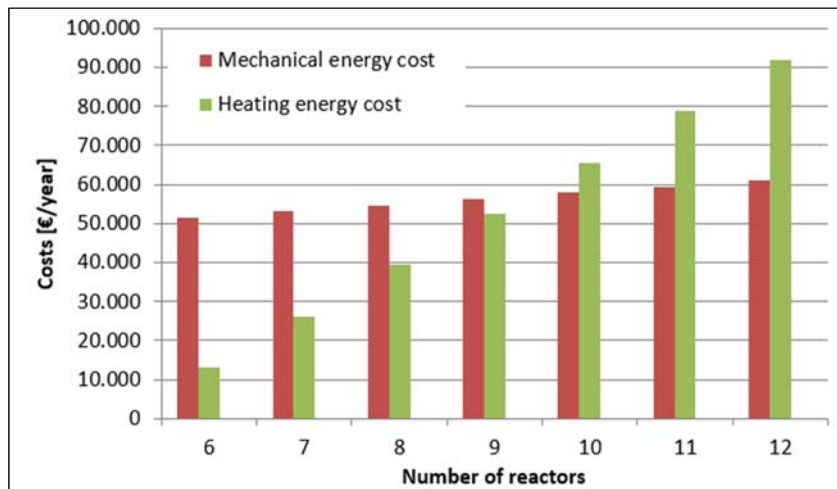**Figure 22 Revenues for sensibility analysis of scenario 1**

Figure 23 Energy costs for sensibility analysis of scenario 1
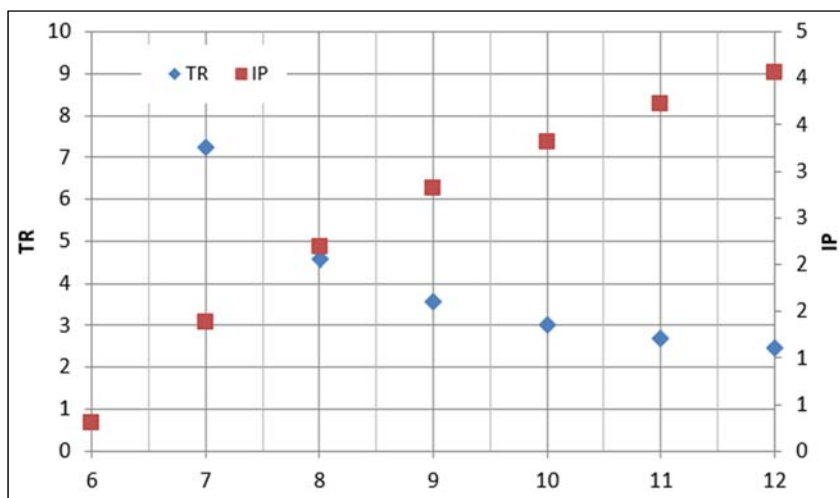

Figure 24 IP and TR for sensibility analysis of scenario 1

Thanks to sensitivity analysis, as shown in the table 12, is possible to verify the modular construction of this type of system.

The process is flexible, in fact the reactor can process variable quantities of organic waste in the time unit, as it is easily scalable, since the number of reactors can be increased without having to make major plant modifications.

Indeed the plant is constituted, in the central section of 'carbonization', by a series of side-by-side modules, which operate in parallel. The initial section, pre-treatment, and the final one, if necessary, drying and pelletizing are common.

It is a very efficient solution to have constructive and operative flexibility, allowing to cut off the system without having to stop it even during maintenance operations. It also makes it easier to adapt the layout of the system to the available spaces.

CONCLUSIONS

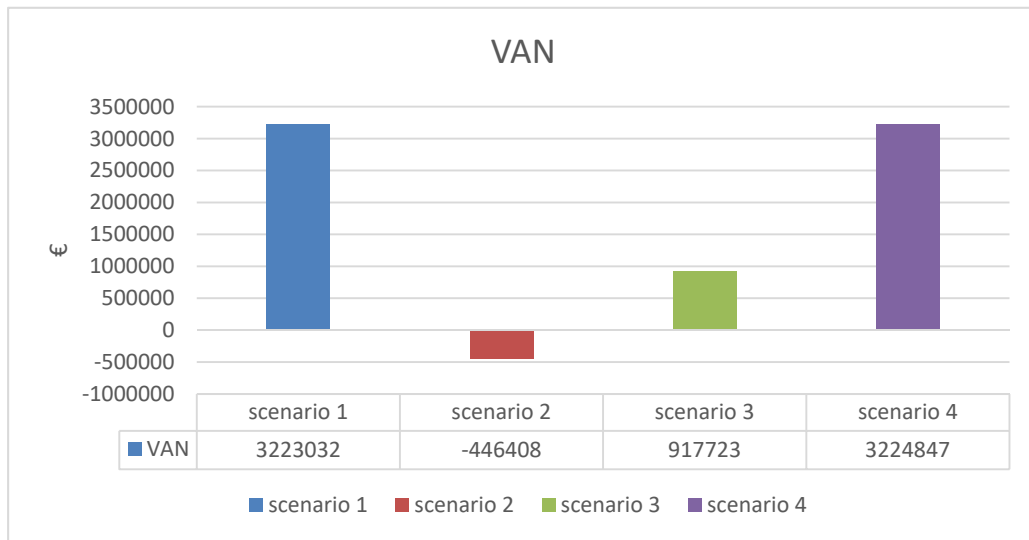The following figures show the results of the different scenarios analysed.

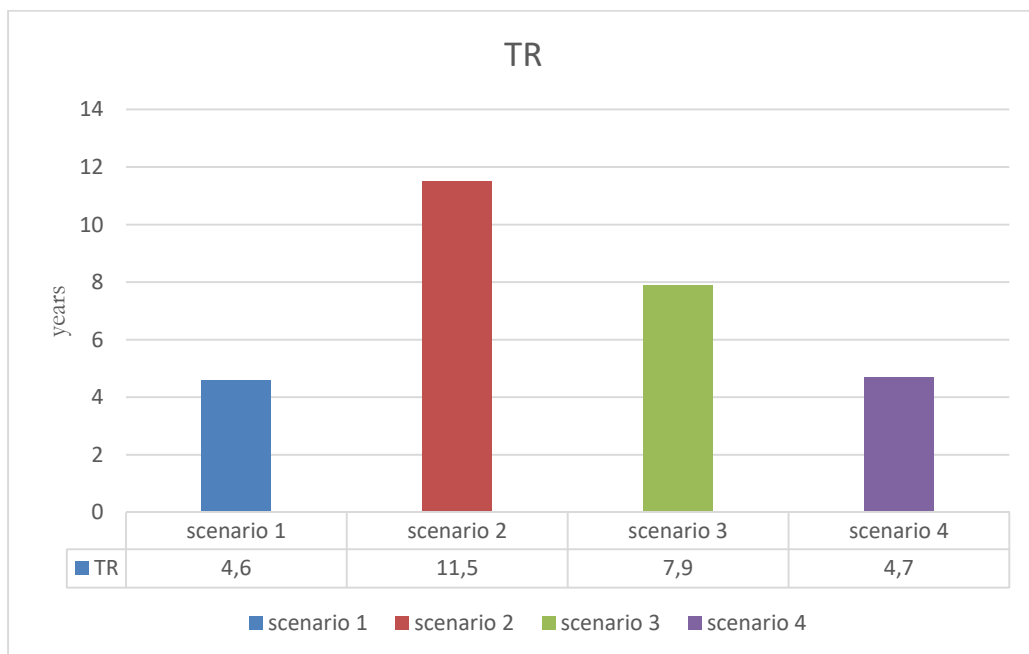**Figure 25 VAN values of different plant scenarios**
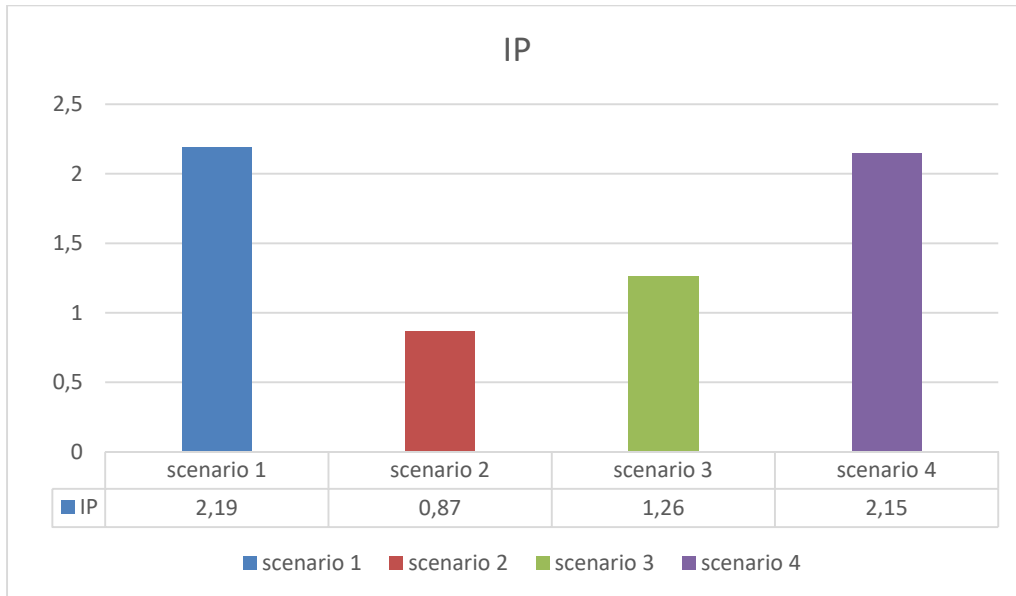

Figure 26 TR values of different plant scenarios

Figure 27 IP values of different plant scenarios

Scenario 1	All the hydrochar produced is sold as pellets; CHP plant is not considered.
Scenario 2	All the hydrochar pellet produced is burned in the boiler for CHP operation, which is included in the financial analysis.
Scenario 3	Half of the hydrochar pellet produced is burned in the boiler for CHP operation in order to meet the electrical requirements of the plant, the remaining half hydrochar is sold as pellets.
Scenario 4	A small part of the produced hydrochar pellet is burned in the boiler for CHP operation in order to meet the thermal requirements of the plant, the remaining hydrochar is sold as pellets; CHP plant for the financial analysis is considered to be of smaller size compared to the other scenarios.

Analyzing the different scenarios, it can be noted that scenarios 1 and 4 are economically advantageous because the results obtained are the configurations that provide the highest values of VAN and IP and the lowest values of TR.

Despite the values obtained, the analysis of the different scenarios was performed with a series of assumptions that could influence the results, in fact the sale of the hydrochar pellet was considered assuming the selling price similar to the price of the pellets EN Plus A1 since there is still no market for this type of product.

Moreover, given the high production of thermal energy by the CHP plant, the best way to exploit it, even through a district heating system, is still under evaluation.

From the type of analysis carried out we can also notice very interesting features such as modularity that allows you to reconfigure and readjust the system, saving money and increasing the value of investment as well as increasing productivity and efficiency while reducing downtime. The adaptability and flexibility of modular solutions therefore offer continuous improvement as changes can be made at any time to reduce unnecessary processes. It has also been seen that the plant needs a reduced manpower because the system is automated, which contributes to the reduction of costs.

From the energetic analysis of the plant, it's possible to notice some very energizing parts are like the drying and pelletizing section, which will then be studied to improve the total efficiency of the system.

Furthermore, we are working on the best solution for the exploitation of the thermal energy produced by the plant through a cogeneration plant, even if this will depend on the final location of the plant.

HTC technology therefore remains an innovative and interesting solution both from a technological and economic point of view, using hydrochar as fuel, which in fact represents one of the main and most technologically mature methods of valorisation, which from an environmental point of view, given that the hydrochar arises, by characteristics, in an intermediate position between compost and biochar. The application of hydrochar on the soil can meet the objectives of fertilization and / or carbon sequestration for the purpose of mitigation of carbon dioxide emissions and constitutes a research field of considerable interest at international level also for the purposes of revisiting the regulations of the law for the application of chars on soils that guarantees the achievement of safety and sustainability objectives.

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