

# A short comparative review of commercial technologies for lignocellulosic biomass pyrolysis in Europe

Cristina Șerbănescu, Aurelia-Mihaela Oprescu

IPROCHIM S. A., Bucharest, Romania. Corresponding author: C. Serbanescu, cristina.serbanescu@iprochim.ro

**Abstract.** Pyrolysis represents an important waste to energy (WtE) thermal method. It has been investigated all over the world especially for economic production of alternative liquid fuels. Lignocellulosic biomass, especially wood, has been widely studied and used at laboratory, pilot or commercial scale due to the ease of comparability between results. Moreover, the concern of converting wood into liquid fuel is a priority for many countries since the first oil crisis in 1973 and the subsequent events of oil price increase in 1990 and energy crisis in 2000s. Generally, two main commercially available lignocellulosic biomass technologies exist depending on the final product envisaged: "slow pyrolysis" for bio-char production and "fast pyrolysis" for bio-oil production. For each of them, dedicated reactor types exist. The European commercial technologies and plants for lignocellulosic biomass are surveyed. Several aspects are summarized: main commercial technologies with corresponding reactor types; product yields and operating conditions; technical-economic aspects; pyrolysis oil characteristics, upgrade and uses; bio-char characteristics and uses. A comparison is made in terms of technico-economic and financial aspects.

**Key Words:** lignocellulosic biomass, wood pyrolysis, fast pyrolysis bio-oil, economic efficiency, bio-char.

**Introduction.** The second half of 20<sup>th</sup> century was marked by several major energy crisis events related to petroleum as a resource. Eversince, many countries are continuously concerned of producing oil and energy from alternative and sustainable sources, like wood for example. Simultaneously, the 21<sup>st</sup> century brought the global concern of wastes and environmental changes mitigation. Meanwhile, energy consumption is a continuous increasing factor since the industrial revolution, in the 19<sup>th</sup> century. In this context, in Europe, a waste management strategy has been elaborated comprising several key Directives. It is the case of Waste Framework Directive, Renewable Energy Directive, Industrial Emissions Directive and of all Directives regarding wastes landfilling. Among them, the Renewable Energy Sources (RES) Directive (Directive 2009/28/EC) and the EC Communication "on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling" (COM(2010)11) recommend the establishment by EU Member States of "national sustainability schemes for solid and gaseous biomass used in electricity, heating and cooling". Nowadays each EU Member State has elaborated a National Renewable Energy Action Plans (NREAPs) defining their share of renewable energy in gross final energy consumption according to Article 4 from RES Directive (Directive 2009/28/EC).

Biomass represents "the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste" (Directive 2009/28/EC). Lignocellulosic biomass is a cheap and abundant resource that was estimated with a potential of providing 13% of the world's energy consumption needs (IEA). It contains three major compounds: cellulose (40-50%), hemicellulose (10-35% in woods, 20-40% in herbaceous biomass) and lignin (20-40% in woods and 10-40% in herbaceous biomass) (Shahzadi et al 2014; Sharma et al 2015). Among them, cellulose is the most abundant component, responsible for biomass' mechanical strength, as it is found predominantly in the cell walls of any plant. Other chemical compounds exist in smaller amounts, depending on the biomass type. These compounds are generally extractives (organic molecules with acetyl/phenolic groups, proteins, salts) and inorganic compounds (mineral substituents, alkali metals – K, Ca, Na, Si, P) (Sharma et al 2015). Lignocellulosic biomass comprises agricultural residues, forestry residues, energy crops and biowaste streams (waste wood, kitchen and garden wastes, cotton residues, sawdust). It will be referred in this paper as 'biomass'.

When regarded as waste, its valorization is made using dedicated *waste-to-energy (WtE)* technologies. Among them, the thermal ones (incineration, pyrolysis, gasification) are preferred due to improved valorization, both material and energetic. Wastes gasification and incineration technologies are the most developed in Europe on a commercial large-scale. Pyrolysis represents the endothermic thermo-chemical decomposition of organic materials at high temperatures in the absence of oxygen or air. It is also referred as 'dry distillation', 'destructive distillation' or 'cracking'. Residual biomass pyrolysis has the advantage of contributing to sustainable use of resources while not interfering with the food chain. Moreover, it is recently preferred due to the production of important and environmental more friendly products (pyrolysis oil and biochar). It has been developed in Europe mainly at research and demonstration scale. The commercial-scale plants are of recent date, in the last 20-30 years. Their usual throughput capacities are of 0.5-10 t/d. An important share of the existing commercial pyrolysis technologies from Europe is represented by imported technologies from other parts of the world, like USA, Canada or Asia. Most of the European great amount of work in this field has been done at a research level (from laboratory scale until pilot and demonstration scales), with few industrial applications. However, local technology providers do exist, mainly in the last 20 years.

Depending on the desired final product, two main pyrolysis processes are used on a commercial scale, having dedicated reactor types: *a) slow pyrolysis* for bio-char production and *b) fast pyrolysis* for bio-oil production. They are differentiated by the operating conditions, mainly by the heating rate and vapors and solids residence times. The key element of any pyrolysis technology is the reactor. The process is endothermic. The necessary thermal energy is ensured either by a heat carrier (hot sand or hot gases) either by indirect heating (heated walls, fuel combustion). For slow pyrolysis, usually batch or continuous kilns are used on an industrial scale: rotary kilns, drum kilns or screw pyrolyzers. The fast pyrolysis process is performed commercially mainly in fluidized-bed bubbling reactors and its more expensive variant, the circulating fluidized-bed reactors. Fluidized-bed reactor types have numerous advantages, the most important being the flexibility of process heating and the lack of needing a circulating gas, as sand is the heat carrier for the process. Other reactor types have been developed on industrial scale for this process: rotating cone, auger (twin-screw), ablative and vacuum systems.

Commercial biomass pyrolysis takes place usually at 450-600°C. Depending on the reactor type, operating conditions and feedstock type, the product yields vary considerably. They usually must be upgraded and further treated in order to have a zero residues process. Pyrolysis as singular process is applied industrially for liquid and solid production. In Europe, the liquid product (fast pyrolysis bio-oil) has been studied, standardized, upgraded and successfully used as fuel in boilers, gas turbines and even Diesel engines. The solid product (bio-char) has been also studied, standardized and used as fuel or as soil amendment in agriculture. Many small-scale mobile biochar production units exist in UK, with a recent dedicated regional standard for this product, i.e. BQM (Biochar Quality Mandate). Other standard exist for biochar characterization that is elaborated for Europe, named EBC (European Biochar Certificate). It is nowadays already applied in Switzerland and Austria. Pyrolysis gases can be further used in a Fischer-Tropsch sequence for hydrocarbons production. They are known as "Fischer-Tropsch Diesel" (2009/28/EC). From an economic point of view, the preferred pyrolysis technology is the fast one with combined heat and power (CHP) production (Bridgwater et al 2002b; Kuppens 2012).

This paper reviews the existing European commercial technologies using lignocellulosic biomass as feedstock. The overviewed technologies are only the operational large-capacity ones, of 0.5-10 t/h feedstock. They are of recent date, i.e. in the last 20-30 years. A comparison is made in terms of technical-economic-environmental aspects. Moreover, the characteristics, uses and some economic aspects for each of the two main biomass pyrolysis products (bio-char and bio-oil) are discussed.

**Commercial lignocellulosic biomass pyrolysis technologies in Europe.** Nowadays in Europe, international organizations and networks working in the pyrolysis field exist. According to a relatively recent overview (San Miguel et al 2012), the largest and most known are: ThermalNet (UK, [www.thermalnet.co.uk](http://www.thermalnet.co.uk)), PyNe (UK, <http://www.pyne.co.uk>) and IEA Bioenergy (European Commission countries and other countries from other parts of the world, [www.ieabioenergy.com](http://www.ieabioenergy.com)). Among them, IEA Bioenergy Task 34 (Pyrolysis), has as overall objective, "to improve implementation and success rate of fast pyrolysis oils for fuels and chemicals by contributing to solving critical technical areas and disseminating relevant information particularly to industry and policy makers. This task aims to monitoring, reviewing, and contributing to solving problems that will permit more successful and more rapid implementation of pyrolysis technology, including identification of opportunities to provide a substantial contribution to bioenergy" (IEA).

Wide research activities for biomass pyrolysis, performed by dedicated groups, exist in Europe. Consequently, several research projects have been financed under FP frameworks, mainly in Estonia, Finland, Latvia, Netherlands, Norway and Sweden. Laboratory research represents the first step in acquiring the commercial scale for a given technology. It is further followed by pilot plant scale and demonstration plants. Biomass pyrolysis is a relatively new concern for Europe. Thus, many projects and installations are found nowadays at these intermediate steps. Commercial-scale plants are scarcely in this part of the world, but huge amounts of research and demonstrations have been made and are continuously made.

The present paper is focused on biomass pyrolysis either for bio-oil either for bio-char production. Pyrolysis gaseous products are usually used within the process. However, if they are further treated for syngas manufacture, wood based Fischer-Tropsch Diesel can be obtained. This type of fuel has the advantage of 95% greenhouse gas emission savings (COM(2010)11). Fast pyrolysis gases are either primary, either secondary (after cracking). Slow pyrolysis gases are similar to the ones from fast pyrolysis process. Primary gases have 11 MJ/m<sup>3</sup> LHV and contain approximately 53% wt CO<sub>2</sub>, 39% wt CO, 6.7% wt hydrocarbons and 0.8% wt H<sub>2</sub> (Vamvuka 2011). Secondary gases may have a LHV of 20 MJ/m<sup>3</sup> and contain approximately 9% wt CO<sub>2</sub>, 63% wt CO, 27% wt hydrocarbons and 1.4% wt H<sub>2</sub> (Vamvuka 2011). As a general rule, the existing biomass pyrolysis technologies are mainly differentiated by the reactor type. Numerous mobile small scale pyrolysis units exist in Europe, mainly for bio-char production. They will not be summarized in this review, although they add a commercial dimension to the pyrolysis technology. A constant concern in EU is given to integrated refinery systems that include pyrolysis. Their main drawback is the extremely high return on investment, up to 300% (PYNE).

On a commercial scale, slow pyrolysis is used for bio-char manufacture while fast and flash pyrolysis for bio-oil and gases production. They are differentiated by the necessary operating conditions. For **slow pyrolysis** is needed a low and moderate decomposition temperature (300-450°C), large particle sizes (0.5-5 cm and even more), slow heating rate (5-60 K/min) and high vapors and solids residence times (7-9 min for vapours and up to 1 hour for solids). For **fast pyrolysis**, the needed conditions are those of high decomposition temperature (400-650°C), fine particle sizes (1 mm and even smaller), rapid heating rates (600–12000 K/min) and very short residence times (0.5-1 s or less than 0.5 s). **Flash pyrolysis** represents a variant of fast pyrolysis using extremely small feedstock particle sizes (< 0.2 mm), very high heating rates (> 1000 K/s) and very short residence times (< 0.5 s) (Jahirul et al 2012). Finely ground feedstock particles (< 2 mm) and small residence times for vapors and solids (< 0.5 seconds) are the key factors for high liquid product yields (≥ 60%). Other factors determining this result include: vacuum pyrolysis process and high carrier gas flow rate (high gas dilution). Meanwhile, the factors determining charcoal as primary product are high process pressure and low gas flow rate. Other factors influencing biomass pyrolysis process are those related to the feedstock's characteristics. Naturally occurring biomass has different sizes (from 1-2 mm to 1-2 cm and even up to meters) and elevated moisture content (usually 10 up to 60% wt. on wet basis). From a practical point of view, it is recommended that the water content of initial feedstock be as low as possible (≤

10%) in order to obtain a high quality for the liquid product and reduce process duration and costs. However, up to 30% moisture can be handled by this type of process (Ronsse 2013).

Theoretically, product yields depend mainly on reaction temperature (Figure 1). Biomass pyrolysis is a very complex process, comprising several physico-chemical stages: primary degradation of solid phase, heat conduction through the solid, heat transfer (conduction, convection, radiation), diffusion and convection of gaseous products, shrinkage and swelling of initial biomass, polymerization and cracking of primary gases, condensation of vapors (Sharma et al 2015). The main drive-force of solids and liquids production is the occurrence of intermediate molten state specie. It has been observed at approximately 430°C for very high heating rates (Vamvuka 2011). During ablative pyrolysis this specie can be clearly observed. Pyrolysis gaseous products comprise non-condensable gases and organic volatile vapors. The latter are responsible for liquid pyrolysis production by condensation when removed from the system. While staying in the system at very high temperatures (> 600°C), they suffer cracking reactions with more non-condensable gases production, together with aromatic compounds (PAHs, PCBs etc.). These compounds enrich pyrolysis char, increasing also its final yield.

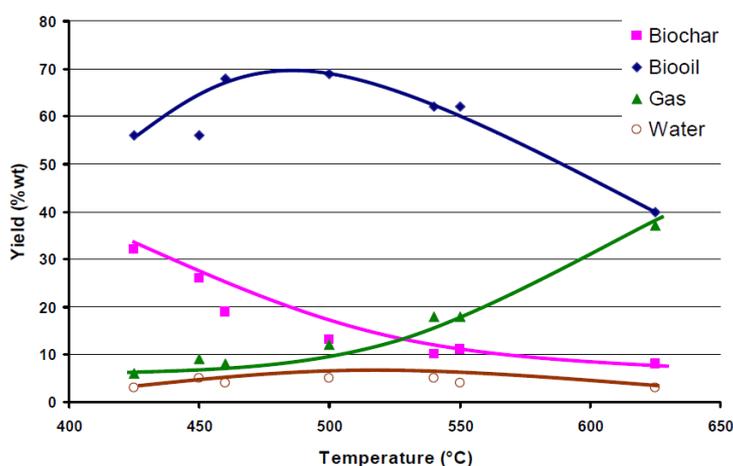


Figure 1. Biomass pyrolysis end product yields vs. reaction temperature (IEA Annual Report 2006).

As can be seen in Figure 1, theoretical maximum liquid (tar, bio-oil) production of 70% is obtained at 450-500°C. When increasing the reaction temperature above these values, the compounds within the tar are cracked and transformed into gases. Thus, the maximum amount of gases, i.e. 40%, is expected at approximately 650°C. Industrially, biomass pyrolysis takes place at 450-500°C. At these temperatures, the usual theoretical product yields are: 70% bio-oil, 18% biochar, 10% gases and 7% water. However, the real pyrolysis temperature is a controversial parameter, as are the heating rate of process and of sample (Lédé & Authier 2015). As (Lédé & Authier 2015) mention, usually what is measured is a mean temperature (fluidized-bed reactors) or even worse, a local temperature (fixed-bed reactors). As a general rule, the real process' temperature is usually uneven distributed among products and parts of the reactor, especially for a slow heat transfer phenomena (pyrolysis kilns) (Lédé & Authier 2015). Consequently, in practice, the product yields are in a higher or lower degree differentiated from the theoretical ones, depending on the operational conditions.

The general flowsheet of any commercial biomass pyrolysis technology (Figure 2) comprises three main systems: biomass pre-treatment, pyrolysis process, downstream processing. In the case of slow pyrolysis process, the last step is represented by heat generation from pyrolysis volatiles (gases, vapors, aerosols) while in the case of fast and flash pyrolysis, it includes two stages, of char removal and vapors quenching.

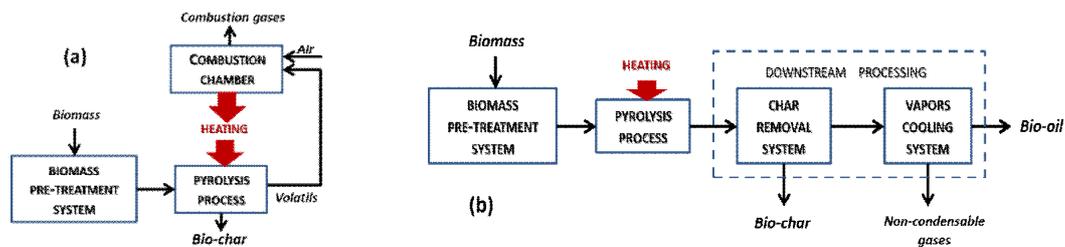


Figure 2. Biomass pyrolysis technology general flowsheet:  
a) slow pyrolysis, b) fast and flash pyrolysis.

Because pyrolysis is an endothermic process, the heating system is an important part of any pyrolysis technology, affecting the economic feasibility of the process. Several types have been developed: hot wall, recycled hot sand, hot fluidizing gas and hot tubes (Chandak 2013). They are specially designed for a certain reactor type, although some flexibility in their choice can be envisaged. A classification of pyrolytic reactors based on the way heat is supplied to biomass has been recently done (Chandak 2013): 1) a part of biomass is burned inside the reactor, 2) direct heating with hot gases from fuel/pyrolysis products burning outside the reactor, 3) contact with hot material (hot gases or sand) into reactor, 4) indirect heating with hot walls from external burning of fuel/ pyrolysis products. Among them, the third type is the most advantageous from a technical-economic point of view.

**Biomass slow pyrolysis technologies in Europe.** Slow pyrolysis of woody biomass is the preferred technology for bio-char production. It has been used by human societies since prehistoric times. Worldwide, more than 197 biochar organizations exist in this specific domain nowadays (Sesko et al 2015). However, commercialization of this technology is not fully realized at large scales. Usual product yields for this type of pyrolysis process are (Ronsse 2013): 30% bio-oil, 35% gases and 35% char. As mentioned before, char represents the primary product of this process. It incorporates within its structure also the ash and other metals from the initial biomass feedstock.

Generally, slow pyrolysis process is the preferred solid wastes thermal valorization technology. It takes place in externally heated rotary drums/kilns. The pyrolysis gas is usually combusted in a high temperature combustion chamber (Kuncser 2011; IEA Annual Report 2013). As an example, in Europe are well-known and developed the pit/mound batch kilns of companies Pressvezz and Carbon Gold from United Kingdom. Other technologies use multistage reactors, where the solid waste and gases have a counter-current movement (Kuncser 2011). Several small-scale mobile units exist in Europe, especially in United Kingdom where this process has been the most developed. As stated before, they will not be considered here. Reactor type is a highly important feature. It must be chosen based on biomass type, morphology and composition, with largest sizes preferred (Ronsse 2013). A mostly known slow pyrolysis technology in Europe is *Pyreg 500*, producing 1 t/d bio-char. It consists of a mobile slow pyrolysis unit with auger and rotating drum reactors (Ronsse 2013). Despite the lower biochar yields obtained (25% wt), it allows a high flexibility in the feedstock due to the mechanical auger.

**Fast pyrolysis technologies in Europe.** Fast and flash pyrolysis are the commonly preferred technologies for biomass valorization and the most developed in Europe and worldwide. This is due to their very important advantage of maximizing bio-oil production. Usual typical product yields for this type of pyrolysis are (Ronsse 2013): 75% bio-oils, 13% gases and 12% char. Even though these technologies have reached nowadays a near-commercial status, they are not at a mature stage, yet. Improvements need to be made in order to decrease the investment costs and to make them financially available for any European country. They are designated by the general term of *BTL*, i.e. "biomass to liquids". It is a process that takes place in several seconds, at relatively high temperatures of 500-600°C and even up to 1000°C. The first major requirement for a

fast pyrolysis reactor is to have a fast heat transfer. This ensures a rapid biomass heating at relatively low temperatures. Secondly, very low vapors residence times are needed for minimizing as much as possible the secondary reactions (San Miguel et al 2011). The most important process parameters to be monitored, as recently proposed, are (Lédé & Authier 2015): *reactor temperature*, *external heat transfer coefficient* and *efficiency of primary products removal* (especially the solid ones). Meanwhile, Lédé & Authier (2015) outline that attention must be paid to all parameters in a global approach that takes into account the linkages existing between reactor properties and particle`s size during the process.

Kuncser (2011) identified 3 main reactor types for fast pyrolysis of wastes: *ablative fast pyrolysis* wherein a centrifugal or mechanical force pressures the material during transformation in order to increase its decomposition rate; *cyclonic (vortex) fast pyrolysis* wherein solids (sand and char) are separated from non-condensable gases and returned to the reactor, and *rotating fast pyrolysis* wherein hot sand and wastes at room temperature are mixed together. Several reactor types were developed worldwide for biomass fast pyrolysis: bubbling fluidized-bed reactor, circulating fluidized-bed reactor, spouted bed reactors, rotating cone reactor, ablative reactors, Auger (twin screw) reactors and vacuum reactors. Each reactor type has specific operational conditions and feedstock requirements, as it can be seen in Table 1.

Table 1  
Main characteristics of biomass fast pyrolysis reactor types (San Miguel et al 2011)

Reactor type	Typical product yield, wt% (tar/char/gas)	Operating temperature (°C)	Gas to biomass ration	Typical feedstock size	Heat transfer coefficient (W/m <sup>2</sup> K)	Maximum plant size
Bubbling fluidized-bed	75/15/10	480	< 2	1-5 mm	150-500	100-200 t/d
Circulating fluidized-bed	78/11/11	520	1.3-1.9	1-10 mm	200-650	100 t/d
Spouted beds	72/12/16	450	< 1	< 3 mm	180-260	25 kg/h
Rotating cone	71/15/14	500	0	< 0.5 mm	500-1500	2 t/h
Ablative reactor (rotating disk)	68/10/22	650	0	chips	502-1675	6-48 t/d
Auger (twin screw)	66/17/17	500	0	sawdust	100-200	12 t/d
Vacuum reactor	56/26/18	475	0	pellets	86-155	3.5 t/h

Regardless the reactor type, usually tar yield is 5-7 times higher than char/gas with several slight differences in the case of ablative, auger and vacuum reactors. The lowest feedstock sizes are needed for the rotating cone reactor while the highest, for the vacuum reactor. This feature lowers the overall investment costs of vacuum reactors, as there is no need for pre-treatment processes of biomass shredding. As expected, the highest heat transfer coefficient value is registered in the case of rotating cone and ablative reactors, followed closely by the fluid bed ones (bubbling fluidized-bed and circulating fluidized-bed). This ensures higher liquid yields and faster process rates. The highest capacities at demonstration and commercial scale were registered for the fluidized-bed type reactors (100-200 tons/day).

Commercial biomass fast pyrolysis was first developed in 1980s in Canada, at the University of Waterloo. The technology is named "Waterloo Flash Pyrolysis Process" (WFPP) (San Miguel et al 2012). Meanwhile, progress has been made. Consequently, several active players already exist in Europe. Depending on the pyrolysis reactor type, the main fast pyrolysis technology developers from Europe are: BTG (Netherlands) and Neste Oil (Finland) for rotating cone reactors; PyTec (Germany) for ablative and twin screw reactors; Fortum (Finland), UPM Biofuels (Finland) and Wellman Process

Engineering Ltd. (UK) for fluidized-bed and circulating fluidized-bed reactors; Bio Oil Holding NV (Belgium) for twin screw and fluidized-bed reactors. As a general rule, Europe is very well represented for fluidized-bed technologies and poorly for non-fluidized bed ones with several exceptions. Catalytic fast pyrolysis in Europe is at its beginnings. At the moment it is in the R&D stage, being difficult to find a suitable and good enough catalyst for obtaining an improved quality bio-oil. Consequently, neither this type of technology shall be overviewed in this paper.

**Biochar characteristics and environmental aspects.** According to IBI (International Biochar Initiative), biochar is defined as *“a solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment”* (Jirka & Tomlinson 2014). Biochar is produced from any carbon rich feedstock, mainly wood and biomass. It is commonly known also as “charcoal”. When not being a primary or co-product of pyrolysis process, biochar is considered a waste. Unfortunately, this is the case in many practical real-market situations. Therefore, its uses must primarily comply with all the existing European waste protocols. Charcoal has been found since prehistoric times in soils, giving birth to a highly fertile type of soil in the Amazon region, named *“terra preta de indio”* (Jirka & Tomlinson 2014). This phenomenon encourages pyrolysis bio-char use in agriculture as fertilizer. Moreover, it represents its major current application. Other uses include: soil remediation, water filtration, solid fuel, and active carbon manufacture for different industries (shoes, pharmaceuticals, foods preservation, supercapacitors). The most important drawbacks for its long-term use in agriculture are related to soil, subsurface and groundwater contamination that may lead to human health hazards and ecosystems damaging (Montanarella & Lugato 2013).

From a 2013 IBI's Report, several European companies were identified for this field, either as biochar producers, either as equipment manufacturers (Jirka & Tomlinson 2014): 3R Environmental Technology Group, EcoEra, Vagga Till Vagga (Sweden); Advanced Gasification Technology, WorldStove (Italy); AVA-CO<sub>2</sub>, CarbonZero, Delinat Institute, Kaskad-E GmbH, Swiss Biochar (Switzerland); Balt Carbon (Latvia); Biochar Ireland (Ireland); Biogreen-Energy, Green Charcoal International (France); BioMaCon, Carbon Terra, ECOSUS Special-Substrates, HydroCarb GmbH, Pyreg (Germany); Cleanfuels, Splainex, Topell Energy (Netherlands); Environmental Power International Ltd, Forest-Char, Four Seasons Fuels, Thompson Spaven, Tigre Energy, Carbon Gold (UK); Global Gateways S.A., Lambiotte & Cie, S.A. (Belgium); Proinso SA (Spain).

A recent study pointed out the existence of important gaps in the European soil legislative framework related to biochar, which is frequently considered as a waste (Montanarella & Lugato 2013). For this reason its use is not legally based in all Member States. Thus, European biochar production and application needs to be enhanced both from technological and legislative points of view. Harmonized and standardized methods must be established. Therefore, a recent European project in this field, REFERTIL project, aims at revising the EC 2003/2003 Fertilizer Regulation with possible inclusion of compost and biochar as organic fertilizers (ABC – animal bone biochar) and soil additives (PCB – plant based biochar containing P and Ca) (Someus 2014). The recommended dose of PCB on soils ranges from 3 up to 20 tons/ha, with an average value of approximately 10 t/ha (Someus 2014). Additionally, this project encourages the establishment of common procedures for EC 764/2008 Mutual Recognition Regulation. This regulation represents is highly important for biochar commercialization within EU. Meanwhile, a European technical standard for biomass based biochar production and quality requirements has been already established. It has a voluntary character, not being an obligation for the industrial manufacturers. However, it is intended to be adopted by all European biochar producers in order to have a unitary market for this product. It is known as EBC, i.e. *“European Biochar Certificate”*. This norm is currently obligatory in Switzerland and Austria for production of biochar intended for agriculture uses. Moreover, biochar EBC certified producers exist also in other European countries. It is the case of Belgium, Germany and Italy. Yet, in Germany, a biochar variety, named “charcoal” is legally used, not having any specific definition or quality requirements. Recently, in 2014, a new standard was established for UK producers. Biochar market is

well developed in this country. The new standard is known as BQM, i.e. “*Biochar Quality Mandate*”. According to EBC, several properties are required for slow pyrolysis biochar in order to be suited for agriculture and other applications, as seen in Table 2 (EBC, 2012). It is important to mention that this norm sets also limited fluctuations in the pyrolysis temperature ( $\leq 20\%$ ) and final biochar composition ( $\leq 15\%$ ) (EBC 2012).

Table 2  
Biochar thresholds and ecological requirements according to EBC norms (EBC 2012)

No.	Characteristic	EBC requirements	
		basic	premium
1	Hg (g/t dry mass)	< 1	< 1
2	Cd (g/t dry mass)	< 1.5	< 1
3	Cr (g/t dry mass)	< 90	< 80
4	Cu (g/t dry mass)	< 100	< 100
5	Pb (g/t dry mass)	< 150	< 120
6	Ni (g/t dry mass)	< 50	< 30
7	Zn (g/t dry mass)	< 400	< 400
8	PCBs (mg/kg dry mass)	< 0.2	< 0.2
9	PAHs (mg/kg dry mass)	< 12	< 4
10	Dioxins/furans (ng/kg dry mass)	< 20	< 20
11	Total C	$\geq 50\%$ (fixed C $\geq 10\%$ )	
12	H/organic C (molar)	$\leq 0.7$	
13	O/C (molar)	$\leq 0.4$	
14	Specific surface ( $m^2/g$ )	$> 150$	

Four main conditions need to be simultaneously met by a biochar in order to receive the EBC level: biomass feedstock type, production method requirements, biochar properties and the applying method (EBC 2012). Biochar quality and safety strongly depends on pyrolysis technology efficiency and working conditions. Key performance indicators are the PAHs levels and H/organic C ratio. High values of PAHs indicate unsatisfactory, obsolete or unsuitable production conditions (EBC 2012). Yet, their measurement is problematic due to the high porosity of pyrolysis biochar. Thus, an initial extraction stage is always required (EBC 2012). Values higher than 0.7 of H/organic C ratio, indicate a char that either is non-pyrolytic, either presents deficiencies (EBC 2012). This factor proves the capability of pyrolysis char to sequester a huge amount of carbon from the initial biomass feedstock. Another important factor is the total carbon content. If lower than 50%, the slow pyrolysis solid product is not classified as biochar, but as “pyrogenic carbonaceous material” (EBC 2012). The EBC norms establish limit values for the most important contaminants, i.e. organic pollutants and toxic elements content. Their amounts depend strongly on the type of initial biomass and on pyrolysis temperature (Libra et al 2011; Vamvuka 2011; Jirka & Tomlinson 2014). Among them, there are four heavy metals considered as priority toxic elements, e.g. Cadmium, Nickel, Lead and Mercury (EBC 2012).

Other norms for biochar characterization exist. It is the case of REACH, i.e. “*Regulation, Evaluation, Authorization and Restriction of Chemicals*” and EC 1907/2006 with its corrigendums. These norms concern biochar manufacturing, importing and placing on the market for production capacities higher than 1 t/yr. Additionally, other physico-chemical properties of pyrolysis biochars include: very high flammability (auto-ignition at 200-250°C), elevated ash content (6-8 times greater than in the initial feed), LHV of about 32 MJ/kg and 15-45% wt. volatile substances (Vamvuka 2011).

Even though all these safety and agronomic efficiency requirements have been established and are even currently used, caution is needed for their systematic use in the agriculture sector. This is due to the irreversible character of its application to soils. As a result, enormous implications may occur from legislative, environmental and human health safety points of view (Montanarella & Lugato 2013). A chemical, physical and

microbiological analysis is recommended before its use on agricultural crops (Someus 2014).

**Pyrolysis Bio-Oil characteristics and environmental aspects.** Fast pyrolysis bio-oil is nowadays a registered substance, having a dedicated CAS number, namely 1207435-39-9. It has been defined by IEA Bioenergy Task 34, by the following statements (PYNE): *"Liquid condensate recovered by thermal treatment of lignocellulosic biomass at short hot vapor residence time (typically less than about 5 seconds) typically at between 450-600°C at near atmospheric pressure or below, in the absence of oxygen, using small (typically less than 5 mm) dry (typically less than 10% water) biomass particles. A number of engineered systems have been used to affect high heat transfer into the biomass particle and quick quenching of the vapour product, usually after removal of solid byproduct "char", to recover a single phase liquid product. Bio-oil is a complex mixture of, for the most part, oxygenated hydrocarbon fragments derived from the biopolymer structures. It typically contains 15-30% water. Common organic components include acetic acid, methanol, aldehydes and ketones, cyclopentenones, furans, alkyl-phenols, alkyl-methoxy-phenols, anhydrosugars, and oligomeric sugars and water-insoluble lignin-derived compounds. Nitrogen- and sulfur-containing compounds are also sometimes found depending on the biomass source."*

Fast pyrolysis bio-oils (FPBO) are generated usually from fast or flash biomass pyrolysis. Their yields depend strongly on feedstock's nature, as well as on reaction temperature, as can be seen in Figure 3 (Oasmaa & Peacocke 2010).

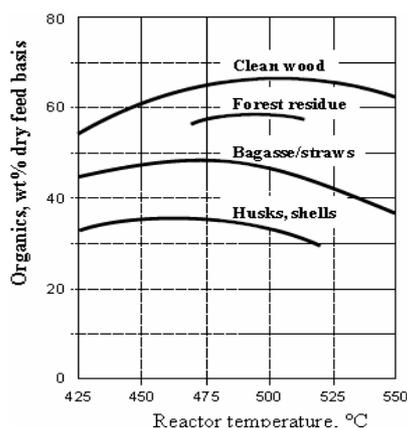


Figure 3. Organic liquid yields approximations for pyrolysis of wood and agro-biomasses (Oasmaa & Peacocke 2010).

It can be observed that higher bio-oil yields are obtained from clean wood rather than from forest residues or straws, while the lowest yields from husks and shells. A chemical formula of wood pyrolysis bio-oil has been established based on ultimate analysis results. This formula ( $\text{CH}_{1.4}\text{O}_{0.6}$ ) proves the existence of approximately 42% oxygen within its structure (Ringer et al 2006). The reference substance for FPBO is benzo[a]pyrene ( $\text{C}_{20}\text{H}_{12}$ ) (ECHA). Different classes of compounds are found within biomass pyrolysis bio-oil (De Wild 2015): 5-10%  $\text{C}_1$  compounds (formic acid, methanol, formaldehyde), 15-35%  $\text{C}_2$ - $\text{C}_4$  aldehydes and ketones (hydroxyl and oxo-substituted), 10-20%  $\text{C}_5$ - $\text{C}_6$  compounds (hydroxyl, hydroxymethyl and/or oxo-substituted furans, furanoses and pyranones), 6-10%  $\text{C}_6$  compounds (anhydrosugars, including anhydro-oligosaccharides), 5-10% water-soluble carbohydrates (oligomers and polymers), 6-15% substituted phenols (methoxyl), 15-30% pyrolytic lignin. More exactly, the highest amounts were found to be those of hydroxyacetaldehyde and aldehydes (10-20% wt.), carbohydrates (levoglucosan, 5-10% wt.), phenols and alcohols (2-5% wt.), acetic acid (5% wt.), formic acid (3% wt.), furfural (1-5% wt.), ketones (1-5% wt.) (Bridgwater et al 2002a; Vamvuka 2011). Other miscellaneous organic compounds can be also found, but in very low concentrations: alcohols, esters, phenols, sugars, furans, alkenes, aromatics, nitrogen compounds, and others (Vamvuka 2011). Commercial FPBO has the following

practical composition (ENSYN): 18.7-65% phenols, 12-15% other organic oxygenates, 0-15% NaOH, 3-10% aldehydes, 3-11% alcohols and sugars and 1.4-6.6% miscellaneous organic compounds (hydrocarbons, ethers, furans and ketones).

A comparison of typical FPBO physico-chemical characteristics (measured by dedicated standardized standards for fuels: ASTM/EN, CEN and ECHA) with those from two major well developed fast pyrolysis technologies and a conventional fuel is given in Table 3. It is clearly seen that, at least for the moment, FPBO is not suited for being used as biofuel in transportation. According to Article 2 of RES Directive (Directive 2009/28/EC) it is classified as "bioliquid". The reason resides in the definitions of *bioliquid* and *biofuel* given by the above-mentioned Directive. Thus, a *bioliquid* is defined as "liquid fuel for energy purposes, other than for transport, including electricity and heating and cooling, produced from biomass" while a *biofuel* is defined as "liquid or gaseous fuel for transport produced from biomass" (Directive 2009/28/EC). In order to obtain a biofuel from FPBO, it is necessary to have it upgraded, i.e. deoxygenated.

Table 3  
Comparison of physico-chemical characteristics of typical standardized FPBO with bio-oils obtained from two major fast pyrolysis technologies and with a conventional Diesel fuel (San Miguel et al 2011; Vamvuka 2011; Wilson et al 2013; ECHA; PYNE)

<i>Physico-chemical property</i>	<i>Typical FPBO CAS 1207435-39-9</i>	<i>Ensyn RTP™</i>	<i>BTG</i>	<i>Conventional diesel fuel</i>
<i>Feedstock</i>	<i>Lignocellulosic biomass</i>	<i>Hardwood</i>	<i>Softwood</i>	<i>-</i>
Average molecular weight	500 - 1000	-	-	~ 200
Density (15 °C), kg/dm <sup>3</sup>	1.10 - 1.30	1.18	1.24	0.82 - 0.86
Viscosity (40 °C), cSt	< 200	11 (50 °C)	105.7	2 - 5
High Heating Value (HHV), MJ/kg	15 - 20	17.0	17.1	45
Water content, wt%	< 40	19.9	18.6	0.05 (v%)
Flash Point, °C	40 - 110	-	-	60
pH	2 - 3.5	3.7	2.7	5
Solids (char and ash), wt%	< 5.5	0.35	-	< 0.01
Alkali (Na+K), ppm	5 - 100	-	-	< 1

Pyrolysis liquids are usually dark red brown to dark green liquids, completely different from petroleum fuels in their physical and chemical composition. It can be observed from Table 3 a significantly lower value for the high heating rate of pyrolysis bio-oils when compared to conventional Diesel fuel. This is due to their extremely high water content of up to 40% wt. Among the two most known commercial fast pyrolysis technologies, BTG oil has lower water content than the one from Ensyn's RTP™ technology: 18.6% wt versus 19.9% wt. This may be due to different biomass types used, i.e. softwood for the first and hardwood for the second. The suspended solids content of FPBO is also relatively high, of 0.05-0.5% wt, when compared to a Diesel fuel (< 0.01% wt). Although a char separation stage is used in the production process, in practice all FPBO have a certain amount of char within their composition influencing their viscosity (Ringer et al 2006). Among these solids, ash is also included. It comprises usually alkaline and/or alkaline-earth metals. Depending on the initial feedstock type, a typical FPBO could contain up to 100 ppm of these metals. Their presence represents a major drawback of biomass fast pyrolysis technologies due to their catalytic behavior which worsens the bio-oil quality. Due to the presence of various organic compounds within their structure, the molecular weight of FPBOs is very high (500 up to 1000) faced to the conventional Diesel fuel (~ 200). This determines densities of 1.1-1.3 kg/dm<sup>3</sup>, higher than those of water or of other conventional fuels. Moreover, pyrolysis oils are more acid than conventional Diesel fuel (2-3.5 pH value). Multiple material safety data sheets for FPBO already exist nowadays in Europe. They represent a supplementary source of characteristics for these compounds. From this additional information it was proved that they are chemically unstable. Thus, they have very short shelf life of several weeks or maybe a few months (Ringer et al 2006; PYNE). Other important characteristics mentioned in the MSDS are the

immiscibility with mineral oils (Ringer et al 2006). For more detailed data on FPBO properties, the works of Oasmaa from the Finnish VTT Group are very relevant (Oasmaa et al 2009).

Many of FPBO characteristics and behaviors put serious problems for their use in automotive engines. It is the case of kinematic viscosity, phase separation (organic-water system) and gum deposition that were observed to increase above one year of storage. Due to their high viscosity, FPBO must be shipped and stored above 50 °C (ENSYN). Soluble ethers, sugar constituents and bio-oils volatility are decreasing in time (Oasmaa & Peacocke 2010; Rasul & Jahirul 2012). A part of these instabilities is explained by the occurrence of chemical reactions within the oil that can be interrupted only by solvents addition (Ringer et al 2006). Usually, a critical HAZOP analysis is recommended before their use as fuel (Ringer et al 2006). More effective however is their upgrade by deoxygenation, representing the preferred industrial choice. Two main processes are nowadays used in this purpose (Elliott 2016): thermal cracking and hydrotreating (HT). The first one has a cheaper variant in the form of catalytic cracking due to low pressure and higher throughput. Bio-oil hydrotreating is similar in operation to petroleum HT, and consists in hydrogen addition. Its catalytic variant is more expensive and the technology is only at bench-scale for the FPBO case (Elliott 2016). More details on bio-oil properties and upgrading methods can be found in a relative recent paper of Bridgwater (2011). At the moment, it is a common practice that all biomass fast pyrolysis plants be equipped with an upgrading system for the resulting bio-oil. Financial more efficient new routes are studied, like the use of red mud as upgrading catalyst for FPBO (Juzsakova et al 2016).

Regarding the environmental impact, FPBO are considered to have a weak or nil toxicological effect (PYNE). However, it was found to be harmful on aquatic life with long lasting effects (ECHA). For human health, the hazards related to this product are: GHS05 (danger or warning corrosive cat. 1), GHS08 (danger or warning, systematic health hazards) and GHS07 (warning toxic cat. 4, irritant cat. 2 or 3, lower systematic health hazards) (ECHA).

Fast-Pyrolysis Bio-Oil has many different applications that have been already used on regular basis: as fuel (after upgrading), for chemicals manufacture (resins, fertilizers, flavors, adhesives, acetic acid), for heating purposes (co-firing of boiler and furnace), for power (Diesel engine and turbines) and in the combined heat and power (CHP) systems (Rasul & Jahirul 2012). Meanwhile, FPBO has been successfully used in several demonstration-scale applications, like (San Miguel et al 2011): preferred choice of co-firing in large power plants of 50 MWe (Netherlands), direct combustion in special boilers for heat generation (adapted for corrosive nature, particle content and high viscosity fuel), slow speed diesel engines (for low grade fuels), gas turbines and in centralized plants for syngas production via gasification.

The main drawbacks of fast pyrolysis bio-oil that prevent them to be commercially more available are (Kuncser 2011; Wilson et al 2013; EBIA; PYNE): environmental, health and safety issues in handling, transport and usage; insufficient studies on the biological and environmental effects of large scale bio-oil production by biomass pyrolysis; lack of sufficient bio-oil supplies for long term testing of their effects in burners; lack of public acceptance of bio-oils due to their distinct and strong odors; uncertain cost of bio-oil; incompatibility of bio-oil with conventional fuels; need of dedicated fuel handling systems.

### **Technical-economic-environmental assessment of commercial biomass pyrolysis technologies from Europe.**

At the level of year 2011, the existing total amount of biomass in EU was of 314.6 Mm<sup>3</sup>/yr with 24% used as firewood (Keränen & Alakangas 2011). Meanwhile, the highest proportion (77%) is used for energy purposes, namely 240.8 Mm<sup>3</sup>/yr or 74.5 Mtoe (Keränen & Alakangas 2011). According to the RES Directive (Directive 2009/28/EC), a total amount of 250 Mtoe energy from renewable sources is desired. However, this amount will not be covered only by biomass. More precisely, the desired share of renewable energy uses are of 46% for heating and cooling, 13% for transport and 42% for electricity (Directive 2009/28/EC).

An estimation for 2020 based on primary energy and corresponding fuel costs from 2010 gave the following mid-term biomass potentials in EU (Pelkmans et al 2012): 77.9 Mtoe/yr and 33 €/MWh-p for agricultural products, 30 Mtoe/yr and 14 €/MWh-p for agricultural residues, 69.7 Mtoe/yr and 21 €/MWh-p for forestry products, 35.8 Mtoe/yr and 9.2 €/MWh-p for forestry residues, 292.2 Mtoe/yr and 19.1 €/MWh-p for solid and gaseous biomass. Therefore, the valorization of such residues into energy, heat and/or useful products is the preferred route for the future of biomass as a renewable source in EU.

In Europe are located approximately 38% of worldwide biochar businesses, especially in UK, Switzerland and Germany (Jirka & Tomlinson 2014). Although industrial biochar production is currently developed in Europe, there is not yet a fully proven technology at large commercial scale. The main barriers for its wider commercial development are (Kuncser 2011; Jirka & Tomlinson 2014; Wilson et al 2013; EBIA; PYNE): lack of consumer and stakeholders awareness, poor access to financing and technological constraints (relatively poor fuel compared to charcoal; contains hazardous pollutants like heavy metals, PCBs and PAHs). Among them, stakeholders' awareness represents a key economic feature for overcoming these difficulties. An intensive and rapidly increased research effort has been made in this area worldwide, with 380 papers published in 2013 and 15% of worldwide projects developed in Europe and UK in this scientific field (Jirka & Tomlinson 2014). Therefore, a wide number of pilot and demonstration plants for biochar production exist in Europe nowadays. Recently, a biochar European technology has been developed. This technology named "3R", is at the moment at a maturity level (TRL9, i.e. ready-for-commercialization status). Its key feature is the rotary kiln reactor of nominal commercial throughput capacities ranging between 6500 t/yr and 20,800 t/yr (Someus 2014). System use is approximately 80%. The 3R technology represents one of the achievements of REFERTIL project, previously mentioned. Another important achievement is the establishment of a permit number for industrial scale pyrolysis plant installation and operation. It has been denominated "FES/01/0851-33/2015" (Someus 2014). Regarding the economic aspects, the estimated 3R's biochar price levels in Europe would be at least 750 €/t (Someus 2014). This corresponds to approximately 179 €/GJ. It is a very expensive price, considering the fact that the average price of EU industrial wood pellets in 2011 was of 106 €/GJ (Keränen & Alakangas 2011). Moreover, the industrial wood chips price in EU in the same year was even smaller. It ranged from 2.5 €/GJ in Portugal to 6.1 €/GJ in Austria (Keränen & Alakangas 2011).

Recent statistic data (Cooper 2015), shows an increase of EU's Diesel demand to approximately 200 mil. t/yr. The highest demands were registered in Western Europe, namely in France (34 mil. t/yr), Germany (33 mil. t/yr), United Kingdom (24 mil. t/yr), Italy (23 mil. t/yr) and Spain (18 mil. t/yr). For the other EU countries, lower demands were registered, i.e. less than 10 mil. t/yr (Cooper 2015). Due to the general context of sustainable development, a replacement of commonly used conventional fuels with renewable ones is desired. Article 17 of Renewable Energy Directive (2009/28/EC) sets sustainability criteria scheme for bioliquids and biofuels. Approx. 5% of current final energy consumption in EU is from bio-energy, with a target of 20% by 2020. Thus, FPBO use in transportation represents a promising route. However, this product must be upgraded in order to have the needed properties. Biomass fast pyrolysis bio-oil is manufactured and imported in UE in quantities of 10,000 up to 100,000 t/yr (ECHA). The most developed commercial technologies for the fast pyrolysis process are the fluidized-bed type ones. Their commissioning is of recent date, since early 2000s. Developments are made continuously in this direction. As an example, the commissioning of another plant similar to the existing one from Joensuu (Finland) is planned for 2016 at Pärnu (Estonia).

Biomass fast pyrolysis plants with CHP production are the most preferred. They are the cheapest ones from investor's point of view, especially at small capacities (1-3 MWe) (Bridgwater et al 2002b; Kuppens 2012). The investment in such installations is highly uncertain and subjected to multiple risks that usually don't fall under the investor's power, like the price of green power certificates, market evolution or feedstock

availability and price (Kuppens 2012). Kuppens recommends changes in inputs/feedstock or in final products proportion, as economic risk reduction actions. Moreover, the environmental and safety aspects must be taken into consideration. Consequently, close attention must be paid to safety and security aspects, by providing a comprehensive hazard identification and risk assessment for each biomass pyrolysis plant. Figure 4 presents a comparison of electricity production costs based on the main thermal WtE technologies using biomass as feedstock (Bridgwater et al 2002a).

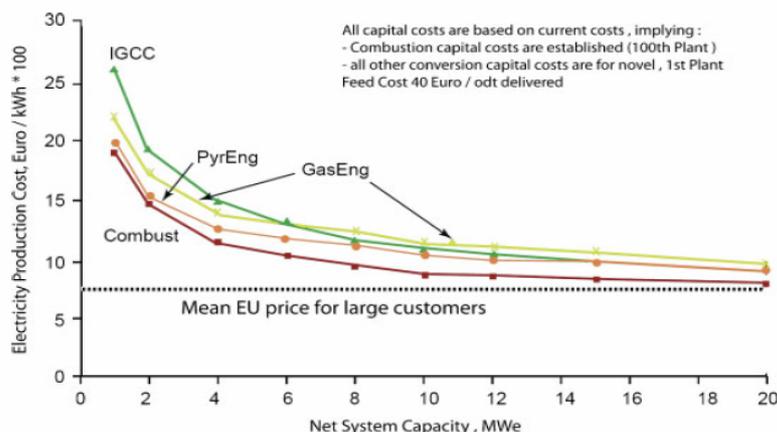


Figure 4. Comparison of electricity production costs based on the main WtE technologies using biomass as feedstock (Bridgwater et al 2002a).

It can be seen that generally, these costs are higher than the mean EU price for the large consumers. Pyrolysis electricity costs for small system capacities (1-3 MWe) are slightly higher than incineration and lower than gasification. For increased plant capacities, incineration remains the most economic choice for electricity production. Several variations exist for each EU Member State due to the specific regional uncertainties (World Energy 2016). Decentralized systems have larger impact in Europe than in other parts of the world (World Energy 2016). Pyrolysis costs per MWh of decentralized systems are decreasing when increasing feed capacity, at amounts significantly lower than those of centralized pyrolysis systems. Additionally, when increasing the pyrolysis plant capacity, the pyrolysis liquids were found to be cheaper. They decreased from approximately 500 €/t for a 250 kg/h plant capacity down to approximately 50-60 €/t for 10 t/h capacity (C.A.R.E. Project). Fiscal incentives for renewable electricity from biomass already exist in all EU Member States, mainly as feed-in-tariffs. Only several countries have the system of green certificates for biomass derived energy, namely Belgium, Poland, Romania, Sweden and UK.

From a very recent EU project (named "BioBoost" project) was found that lowest production costs (average annual profits of 2500 €/ton) could be obtained when using straw as feedstock in three European countries, i.e. Hungary, Poland and Romania (Hagen et al 2015). In general terms, FPBO price is highly dependent on feedstock costs as well as on the process overall efficiency (Ringer et al 2006). Its calculus is based on electricity costs and especially on the operating conditions, namely feedstock moisture (if high, supplementary costs are needed for its drying), operating hours (batch or continuous process), reactor type, feedstock throughput inside the reactor, type of heating system and supplementary systems needed for char and liquid final production (elevated price if upgrade and/or post-treatment are needed). The reference prices in 2010 in EU for electricity, heat and transport fuels were (Pelkmans et al 2012): 54.9 €/MWh electricity (whole sale), 40 €/MWh heat (grid-connected), 73.3 €/MWh heat (decentral) and 44.3 €/MWh transport fuel.

The general mathematical calculus of any biomass pyrolysis production unit costs uses the following sub-costs in various financial formulas (Bridgwater 1991): biomass production, solid transportation, feedstock's size reduction, feedstock drying, bio-oil transportation, upgrading and refining. Based on these sub-costs, other costs can be calculated, like bio-oil production, crude hydrocarbons and refined hydrocarbons

(Bridgwater 1991). Meanwhile, other factors related to long-term biomass-based plant operation must be taken into account for the total project investment cost calculation (Wright et al 2010): general plant depreciation period, plant recovery period and life, financing rate (where applicable), financial and legislative incentives.

The representative operational commercial large-scale facilities for biomass fast pyrolysis in Europe at the moment are listed in Table 4. The status of technology considered in this list is of minimum first commercial application (2-20 t/h), designated as TRL 8 by the EC norms. The reactors for commercial biomass fast pyrolysis operate at 400-600°C and are using woody biomass as feedstock. As expected, the bio-oil yield is differentiated by the reactor types: 75% for bubbling fluidized-bed reactors and circulating fluidized-bed reactors; 65% for rotating cone reactors (RCR) and only 60% for ablative reactors (Vamvuka 2011; San Miguel et al 2012).

Table 4

Representative biomass fast pyrolysis commercial operational plants in Europe  
(PYNE, San Miguel et al 2011; San Miguel et al 2012)

<i>Location</i>	<i>Technology provider</i>	<i>Technology</i>	<i>Capacity and main product</i>	<i>Specific investment cost (€/t)</i>
Oldbury (England) Since 2002	Wellman Process Engineering Ltd.	<u>Circulating fluidized bed</u> 500°C; char and gases burned; 12 wt% char; 14 wt% gas	10 t/h softwood chips 7 t/h bio-oil	273
Bülkau (Germany) Since 2006	PYTEC	<u>Ablative rotating disk reactor</u> <u>BTO technology</u> 450-700°C; 300 kWe CHP Diesel; char partly burned; 30-50 bars	6 t/h chipped softwood and straw; 3.9 t/h bio-oil	42
Porvoo (Finland) Since 2007	Neste Oil	<u>Rotating cone refinery</u> (75% use); VOC emissions and leaks detecting; sulphur recovery; water treatment units	13 mil. t/yr wood residues; 5 mil t/yr NExBTL renewable Diesel fuel	2
Tampere (Finland) Since 2009	VTT & Fortum	<u>Fluidized bed</u> 500°C; very fine particle sizes (< 5 mm); special fluid -bed boilers	10 t/h wood (forest residues, sawdust) 6.3 t/h bio-oil	101
Tesseenderlo (Belgium) Since 2010	Bio Oil Holding	<u>Twin screw and fluidized bed</u> 400-650°C, 1-5s residence time; char partly burned; gases in CHP	5 t/h biomass	101
Delfzijl (Netherlands) Since 2010	Bio Oil Holding	<u>Twin screw and fluidized bed</u> 400-650°C, 1-5s residence time;	5 t/h biomass	202
Hengelo (Netherlands) Since 2010	BTG & Emyro	<u>Rotating cone</u> Char and gases burned; electricity and process steam production	5 t/h clean wood, organic residues and wood pellet waste; 3.2 t/h bio-oil	479
Jelgava (Latvia) Since 2013	Fortum	<u>Circulating fluidized bed</u> 500°C; gases used in CHP (up to 85% of district heating); 23 MWe and 45 MW heating	100,000 t/yr wood chips 110 GWh elect/yr 213 GWh heat/yr	700
Laappeenranta (Finland) Since 2015	UPM Biofuels	<u>Circulating fluidized bed</u> world's first wood-based renewable diesel <u>biorefinery</u>	0.13 mil. t/yr wood 100,000 t/yr BioVerno Diesel	1312
Joensuu (Finland) Since 2015	Fortum	<u>Fluidized bed refinery</u> ; catalytic process; 210 GWh CHP production; 55 MWe; 110 MW heating	600,000 m <sup>3</sup> /yr forest residues, wood wastes, sawdust; 50,000 t/yr Fortum Otso® bio-oil	52.5

As can be seen, bubbling fluidized-bed technology is the cheapest and most profitable one, while circulating bed is the most expensive in terms of total investment costs. Very low investment is also needed for RCR technology from BTG provider. The highest investment costs (175 mil. €) was made in 2015 for the world's first wood-based bio-Diesel refinery in Finland, using a circulating-bed reactor, at Laappeenranta in Finland, producing 100,000 t/yr liquid named BioVerno Diesel. This type of Diesel can be successfully used in any Diesel type engines.

According to San Miguel et al (2012), the capital investment required for a fast pyrolysis plant with CHP is of 200-500 €/kW, depending on the scale and technology

used. For increased biomass pyrolysis plant capacities higher total capital investment costs are expected, namely in the approximate range of 8800 € – 44 million € for capacities of 2.4 t/d up to 1000 t/d (Ringer et al 2006). This corresponds to a range of 0.027 – 133 €/t specific investment costs for a plant having 1000 t/d capacity. An average sized 100 MW plant would need an investment cost of 20-50 mil. €. Usually, biomass cost varies significantly in Europe, from 1 to 100 €/t and is influenced by the prices of related industrial markets (BFH 2007; ALTENERIIR Report). From Table 4 can be observed that usually, the investment cost is higher than biomass cost and higher even than literature registered values. It is mainly the case of non-fluidized-bed reactors. This outlines once again their effectiveness in terms of economic efficiency. As mentioned before, supplementary costs must be taken into account. More precisely they must include (Wright et al 2010; San Miguel et al 2012): biomass purchase and delivery; transportation, storage and pre-treatment costs; equipment purchase, delivery and installation costs, operating costs (labour, consumption related costs, insurance, administrative costs, contingencies, maintenance); general overhead (safety, general engineering, general plant maintenance, payroll overhead, plant security, phone, light, heat and plant communications); contingency factors to installed equipment; insurance and taxes. A key factor is represented by the efficiency of the considered pyrolysis technology. Consequently, BioBoost project recommends the taking into account of a dynamic economic environment for mid and long term residual biomass pyrolysis process, with high value by-products (Hagen et al 2015).

Bio-oil price was found to decrease when increasing pyrolysis plant capacity (from 2.4 t/d up to 1000 t/d) (Ringer et al 2006). It is found usually in the range of 90-330 €/t for a feedstock price of 0.97-1.93 €/GJ (Ringer et al 2006). It was estimated to be the highest price of biofuels, higher even than bio-ethanol (Gust et al 2005). Production cost of FPBO varies between 60 and 200 €/t, corresponding to approximately 4-15 €/GJ (San Miguel et al 2012).

When comparing the reactor types needed for biomass pyrolysis, their technological advantages and disadvantages must be considered. For biochar production, the most used large-scale technology is named "Pyreg 500". It uses auger and rotating drum reactors. It already has multiple commercial implementations in Europe. Its main advantages include (Ringer et al 2006; Oasmaa & Peacocke 2010; Vamvuka 2011; Chandak 2013; Ronsse 2013; PYNE): high degree of process control, residual heat recovery for biomass drying and/or domestic heating, continuous process, use of mechanical force to move the solid material, feedstock flexibility regarding its morphology. However, several disadvantages exist: occurrence of backmixing, extensive attrition and safety risks due to large quantities of fines (Ringer et al 2006; Oasmaa & Peacocke 2010; Vamvuka 2011; Chandak 2013; Ronsse 2013; PYNE). Fast pyrolysis reactors have the advantages and disadvantages given in Table 5. It can be observed that fluidized-bed reactors and entrained-flow ones are easiest to scale-up to a commercial level (Vamvuka 2011). This is the reason why they are more industrially achievable. Although the rotating cone BTG technology is a well-known and used technology, it remains a very costly one. Meanwhile, the reactors containing many mechanical parts are subjected to char abrasion. As a conclusion, the preferred ones in terms of technological effectiveness are the fluidized-bed reactors, being the most developed technology nowadays for biomass pyrolysis. They have the major advantage of equipment manufacturers existence, as they represent a reactor type widely used for gasification and incineration processes.

There are several great advantages for fast pyrolysis implementation in Europe and in EU countries (Hagen et al 2015): approximately 25,000 jobs will be created in the agricultural sector of the East-European countries, a total of 19.2 Mton CO<sub>2</sub> reduction and 1% fuel replacement with biofuel from straw fast pyrolysis. In many EU Member States (Austria, Denmark, Germany, Ireland, Italy, Luxembourg, Portugal, Spain, United Kingdom) special prices offered for renewable electricity, including the biomass related sources exist, with an average value of 0.05 €/kWh (ALTENERIIR Report). These incentives are stimulating electricity production from renewable sources with biomass included but not as a major part.

Table 4

Fast pyrolysis reactors specificities (Ringer et al 2006; Oasmaa & Peacocke 2010; Vamvuka 2011; Chandak 2013; Ronsse 2013; PYNE)

<i>Advantages</i>	<i>Disadvantages</i>
<i>Bubbling Fluidized Bed Reactor</i>	
<ul style="list-style-type: none"> <li>- well understood technology (simple to design, construct and operate and ease of scaling)                             <ul style="list-style-type: none"> <li>- good solids (hot sand and biomass) mixing;</li> </ul> </li> <li>- good heat transfer (150-500 W/m<sup>2</sup>K), temperature control and flexible heating methods;                             <ul style="list-style-type: none"> <li>-no inert gas needed (reduced size and cost of bio-oil collection system);</li> </ul> </li> <li>- char can be catalyst for vapor cracking, short vapors residence times and 75% wt bio-oil</li> </ul>	<ul style="list-style-type: none"> <li>- particulates size ≤ 3 mm;</li> <li>- char can be accumulated at the top of the bed</li> </ul>
<i>Circulating Fluidized Bed Reactor (RTP™ technology)</i>	
<ul style="list-style-type: none"> <li>- simple to design, construct and operate and ease of scaling;                             <ul style="list-style-type: none"> <li>- good solids (hot sand and biomass) mixing;</li> </ul> </li> <li>- good heat transfer (200-650 W/m<sup>2</sup>K), temperature control and flexible heating methods;                             <ul style="list-style-type: none"> <li>- large heat storage capacity;</li> <li>- no inert gas needed (reduced size and cost of bio-oil collection system);</li> </ul> </li> <li>- char can be catalyst for vapor cracking, short vapors residence times and 75% wt bio-oil</li> </ul>	<ul style="list-style-type: none"> <li>- shorter residence times implying higher char content in bio-oil;                             <ul style="list-style-type: none"> <li>- particulates size ≤ 2 mm;</li> </ul> </li> <li>- increased complexity of the system;                             <ul style="list-style-type: none"> <li>- char attrition;</li> <li>- reactor wear</li> </ul> </li> </ul>
<i>Ablative Rotating Disk Reactor (PyTec™ -BTO technology)</i>	
<ul style="list-style-type: none"> <li>- no inert gas needed (reduced size and cost of bio-oil collection system);                             <ul style="list-style-type: none"> <li>- lower reaction temperature;</li> <li>- larger sizes of biomass feedstock;                                     <ul style="list-style-type: none"> <li>- compact design;</li> <li>- intensive system</li> </ul> </li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>- reaction rate strongly depending on pressure, wood relative velocity on the heat exchange surface and on reactor surface temperature;</li> <li>- char abrasion and excessive wear (mechanically more complex);                             <ul style="list-style-type: none"> <li>- high heat transfer requirements (502-1675 W/m<sup>2</sup>K);</li> <li>- costly scaling</li> </ul> </li> </ul>
<i>Rotating Cone Reactor (BTG technology)</i>	
<ul style="list-style-type: none"> <li>- no inert gas needed (reduced size and cost of bio-oil collection system);</li> <li>- good mixing of solids and high throughput capacity (up to 3 kg/s);                             <ul style="list-style-type: none"> <li>- relatively easy scaling and small investment costs;</li> </ul> </li> <li>- reduced wear problems (less aggressive transport dynamics)</li> </ul>	<ul style="list-style-type: none"> <li>- heat transfer needs to be proved at large scale;                             <ul style="list-style-type: none"> <li>- uncertain scale-up issues;</li> <li>- complex integrated process;</li> </ul> </li> <li>- high investment and maintenance costs;</li> </ul>
<i>Auger (Twin Screw) Reactor</i>	
<ul style="list-style-type: none"> <li>- low char content in the final bio-oil;</li> <li>- use of mechanical force to move the solid material</li> </ul>	<ul style="list-style-type: none"> <li>- occurrence of backmixing and extensive attrition;</li> <li>- safety risk due to large quantities of fines</li> </ul>
<i>Vacuum Reactor</i>	
<ul style="list-style-type: none"> <li>- clean bio-oil (low char quantity, easier condensation);                             <ul style="list-style-type: none"> <li>- larger size of particulates (up to 5 cm);</li> </ul> </li> <li>- no inert gas needed (reduced size and cost of bio-oil collection system);                             <ul style="list-style-type: none"> <li>-lower reaction temperature needed</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>- lower bio-oil yields (60% wt.) with more water (scrubbers needed);                             <ul style="list-style-type: none"> <li>- low heat transfer rates (86-155 W/m<sup>2</sup>K);</li> <li>- high solids residence times;</li> </ul> </li> <li>- high investment and maintenance costs</li> </ul>

**Conclusions.** Biomass pyrolysis is applied at commercial scale either for bio-oil either for biochar production. The needed biomass can be residual non-food one, which represents a major advantage of this waste-to-energy process. In Europe already exists a continuous concern for this type of wastes pyrolysis due to the energetic valorization occurring. Therefore, the Renewable Energy Sources Directive sets the shares of biomass energy for each EU country. Among the thermal valorization technologies, pyrolysis represents a promising route, usually used in an integrated system, as a stage of wastes treatment.

A cheap liquid bio-fuel is obtained from biomass fast pyrolysis. However, many challenges exist for this product, like immiscibility with fossil fuel oils, highly acidic, contains approximately 30% water, has low HHV, and relative high density and viscosity and is extremely unstable in time. Progress has been made in Europe under the International Energy Agency (IEA) Bioenergy Agreement, Task 34, regarding its standardization. Thus, fast pyrolysis bio-oil is actually defined with a CAS number (1207436-39-9) and ASTM standards (D-7544 and D-7579). Slow pyrolysis gives as main product the biochar, a very efficient soil amendment for agriculture purposes. This technology is most developed in UK. Moreover, a European technical standard (EBC, European Biochar Certificate) for biochar quality requirements needed for its use in agriculture has been established and even applied as an obligation norm in Switzerland and Austria. In Germany a type of biochar generally designated as "charcoal" is applied without any specific definition or quality requirements.

Generally, the existing operational commercial plants in Europe are of relatively recent date, since early 2000s. Among the various reactor types developed for fast pyrolysis, fluidized-bed ones are the easiest to scale-up to a commercial level (Vamvuka 2011). This is the reason why they are more industrially achievable. The usual capacities of these plants vary between 250 kg/h and 20 t/day. The highest investment costs (175 mil. € and 1312 €/t) was made for the world's first wood-based bio-Diesel refinery in Finland, using a circulating-bed reactor, at Lappeenranta (Finland) producing 100,000 t/yr bio-Diesel. The produced bio-oil, called "BioVerno Diesel", can be successfully used in any Diesel type engine.

The capital investment cost required for a fast pyrolysis plant is of 200-500 €/kW and 50-200 €/t of biomass, depending on the scale and the technology used. BioBoost project recommends for mid and long term utilization of residual biomass pyrolysis, to consider a dynamic economic environment and to have a production technology with high value by-products.

The valorization of biomass into bio-oil and biochar represents a profitable new industrial sector that creates new jobs even in low developed countries or in economically difficult times. However, studies and improvements are needed because pyrolysis products put serious problems from the point of view of environment protection and public health.

## References

- Bridgwater A. V., 1991 Integrated liquid fuel processes. In: Biomass pyrolysis liquids upgrading and utilization. Commission of the European Communities. Bridgwater A. V., Grassi G. (eds), Elsevier Applied Science, 400 pp.
- Bridgwater A. V., 2011 Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy, pp. 1-27.
- Bridgwater A. V., Czernik S., Piskorz J., 2002a The status of biomass fast pyrolysis. Fast Pyrolysis of Biomass: A Handbook, volume 2, Newby, CPL2, pp. 1-22.
- Bridgwater A. V., Toft A. J., Brammer J. G., 2002b A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable and Sustainable Energy Reviews 6(3): 181-246.
- Chandak S. P., 2013 Biomass pyrolysis. Training on technologies for converting waste agricultural biomass into energy. United Nations Environment Programme (UNEP DTIE IETC), 23-25 September 2013, San Jose, Costa Rica, URL: <http://slideplayer.com/slide/6251498/>.

- COM(2010)11, 2010 Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling. European Commission, Brussels, Belgium, 20 pp.
- Cooper J., 2015 Statistical Report 2015. Fuels Europe, <https://www.fuelseurope.eu/uploads/Modules/Resources/fuelseurope-statistical-report-2015.pdf>.
- De Wild P. J., 2015 Biomass pyrolysis for hybrid biorefineries. In: Industrial biorefineries and white biotechnology. Pandey A., Hofer R., Larroche C., Taherzadeh M., Nampoothiri K. M. (eds), Elsevier, Amsterdam, Netherlands, 681 pp.
- Directive 2009/28/EC, 2009 "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequent repealing Directives 2001/77/EC and 2003/30/EC", Official Journal of the European Union, 47 pp.
- EBC, 2012 European Biochar Certificate – Guidelines for a Sustainable Production of Biochar, European Biochar Foundation (EBC), Arbaz, Switzerland, version 6.2E of 4<sup>th</sup> February 2016, URL: <http://www.europeanbiochar.org/en/download>.
- Elliott D. C., 2016 Transportation fuels from biomass via fast pyrolysis and hydroprocessing. In: Advances in bioenergy. The sustainability challenge. Lund P. D., Byrne J., Berndes G., Vasalos I. A. (eds), Wiley, West Sussex, United Kingdom.
- Gust S., Mc Lellan R. J., Meier D., Oasmaa A., Ormrod D., Peacocke G. V. C., 2005 Determination of norms and standards for bio-oil as an alternative renewable fuel for electricity and heat production. In: Fast pyrolysis of biomass - a handbook. Bridgwater A. V. (ed), vol. 3. CPL Press: U.K.
- Hagen E., Konst P., Van Horssen A., 2015 Deliverable 6.5. "Market implementation plan". BioBoost project ("Biomass based energy intermediates boosting biofuel production"), grant agreement no. 282873.
- IEA Annual Report, 2006 "IEA Bioenergy: Task 34, Pyrolysis of Biomass", International Energy Agency, Paris, France.
- IEA Annual Report, 2013 "IEA Bioenergy: EXCO: 2014: 01", IEA Headquarters, Paris, France.
- Jahirul M. I., Rasul M. G., Chowdhury A. A., Ashwath N., 2012 Biofuels production through biomass pyrolysis – a technological review. *Energies* 5:4952-5001.
- Jirka S., Tomlinson T., 2014 2013 State of the biochar industry. A survey of commercial activity in the biochar field. International Biochar Initiative (IBI), 61 pp.
- Juzsakova T., Rédey Á., Fráter T., Le Phuoc C., Németh J., Sebestyén V., 2016 Study on the catalytic activity and surface properties of the red mud. 11<sup>th</sup> International Conference ELSEDIM – Building Disaster Resilience in a Changing World, 26-28 May, Babeş-Bolyai University, Cluj-Napoca.
- Keränen J., Alakangas E., 2011 Report on the competition and price situation of woody biomass use in forest industry and energy sector, EUROBIONET 3 project, VTT-R-02376-11, Jyväskylä, Finland.
- Kuncser R., 2011 Contribution to the study of production and combustion in Diesel engines of pyrolysis oils from thermoplastic wastes [Contribution à l'étude de la production et de la combustion en moteur Diesel d'huiles de pyrolyse de déchets thermoplastiques]. PhD thesis, Nantes University, France, 149 pp.
- Kuppens T., 2012 Techno-economic assessment of fast pyrolysis for the valorization of short rotation coppice cultivated for phytoextraction. PhD thesis, Hasselt University, Diepenbeek, Belgium, 389 pp.
- Lédé J., Authier O., 2015 Temperature and heating rate of solid particles undergoing a thermal decomposition. Which criteria for characterizing fast pyrolysis? *Journal of Analytical and Applied Pyrolysis* 113:1–14.
- Libra J. A., Ro K. S., Kammann C., Funke A., Berge N. D., Neubauer Y., Titirici M. M., Fühner C., Bens O., Kern J., Emmerich K. H., 2011 Hydrothermal carbonization of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis. *Biofuels* 2(1):89-124.

- Montanarella L., Lugato E., 2013 The application of biochar in the EU: challenges and opportunities. *Agronomy* 3:462-473.
- Oasmaa A., Peacocke C., 2010 Properties and fuel use of biomass derived fast pyrolysis liquids. A guide. VTT Publications 731, 134 pp.
- Oasmaa A., Elliott D. C., Müller S., 2009 Quality control in fast pyrolysis Bio-Oil production and use. *AIChE*.
- Pelkmans L., Devriendt N., Junginger M., Hoefnagels R., Resch G., Matzenberger J., Kranzl L., Panzer C., Diaz-Chavez R., Rosillo-Calle F., Hennenberg K., Wiegmann K., Herrera R., Fritsche U., Cocchi M., Bálint J., 2012 Benchmarking biomass sustainability criteria for energy purposes. Final Report, Contract ENER/C1/495-2009/SI2.572581, 120 pp.
- Rasul M. G., Jahirul M. I., 2012 Recent developments in biomass pyrolysis for bio-fuel production: its potential for commercial applications. In: *Recent Researches in Environmental & Geological Sciences, Proceedings of the 7<sup>th</sup> WSEAS International Conference on Energy & Environment (EE'12)*, WSEAS Press, Kos Island, Greece. Atwell N., Volkov K., Matos C., de Arroyabe P. F. (eds). Available at: <http://www.wseas.us/e-library/conferences/2012/Kos/WEGECM/WEGECM-38.pdf>.
- Ringer M., Putsche V., Scahill J., 2006 Large-scale pyrolysis oil production: a technology assessment and economic analysis. Technical Report NREL/TP-510-37779, National Renewable Energy Laboratory, Colorado, USA.
- Ronsse F., 2013 Report on biochar production techniques. A publication of the Interreg IVB project Biochar: climate saving oils.
- San Miguel G., Makibar J., Fernandez-Akarregi A. R., 2011 New advances in the fast pyrolysis of biomass. *Proceedings of the 12th International Conference on Environmental Science and Technology*, Rhodes, Greece, A1615-1622.
- San Miguel G., Makibar J., Fernandez-Akarregi A. R., 2012 New advances in the fast pyrolysis of biomass. *Journal of Biobased Materials and Bioenergy* 6: 1-11.
- Sesko M., Shearer D., Stangl G., 2015 Commercialization of the biochar industry. In: *Biochar for environmental management. Science, technology and implementation. Second Edition*, Lehman J., Joseph S. (eds), Routledge, New York, USA, 976 pp.
- Sharma A., Pareek V., Zhang D., 2015 Biomass pyrolysis – a review of modelling, process parameters and catalytic studies. *Renewable and Sustainable Energy Reviews* 50:1081-1096.
- Shahzadi T., Mehmood S., Irshad M., Anwar Z., Afroz A., Zeeshan N., Rashid U., Sughra K., 2014 Advances in lignocellulosic biotechnology: a brief review on lignocellulosic biomass and cellulases. *Advances in Bioscience and Biotechnology* 5(3):246-251.
- Someus E., 2014 Terra Humana and Wessling Ltd., Grant Agreement no. 289785, Deliverable D 2.3. – “Biochar policy supporting report, concerning the absence of potential risks for the different environmental compartments, for the plants and for human health through the food chain resulting from the use of these materials in agricultural soils”, REFERTIL project – “ Reducing mineral fertilizers and chemicals use in agriculture by recycling treated organic waste as compost and bio-char products”.
- Vamvuka D., 2011 Bio-oil, solid and gaseous biofuels from biomass pyrolysis processes – an overview. *International Journal of Energy Research* 35:835-862.
- Wilson B., Williams N., Liss B., Wilson B., 2013 A comparative assessment of commercial technologies for conversion of solid waste to energy. *Enviro Power Renewable Inc.*, 41 pp.
- Wright M. M., Satrio J. A., Brown R. C., Daugaard D. E., Hsu D. D., 2010 Biomass fast pyrolysis to transportation fuels. Technical Report, NREL/TP-6A20-46586, US Department of Energy, 73 pp.
- World Energy, 2016 A climate of innovation – responding to the commodity price storm, World Energy Council. Available at: <http://www.worldenergy.org/wp-content/uploads/2016/03/2016-World-Energy-Issues-Monitor-Full-report.pdf>.
- \*\*\*ALTENERIIR Report, C.A.R.E. Project, Ireland. Available at: <http://www.care.demon.co.uk/ALTENERIIRReportFinalv10.pdf>

- \*\*\* BFH, 2007, vol. 45(2), Available at: [http://www.nova-institut.de/news-images/20070810-05/qb2007\\_2.pdf](http://www.nova-institut.de/news-images/20070810-05/qb2007_2.pdf)
- \*\*\* C.A.R.E. Project, Ireland, Available at: <http://www.care.demon.co.uk/projectprofile07.pdf>.
- \*\*\* EBIA, 2016, European Biomass Industry Association. Available at: <http://www.eubia.org/index.php/about-biomass/pyrolysis-and-gasification/pyrolysis>.
- \*\*\* ECHA, 2016, Fast Pyrolysis Bio-oil, Guidance on safe use. Available at: <http://echa.europa.eu/registration-dossier/-/registered-dossier/12235/9>.
- \*\*\* ENSYN, wood pyrolysis material safety data sheet. Available at: [http://www.sfm.state.or.us/CR2K\\_SubDB/MSDS/LIQUID\\_ENSYN\\_MNRP.PDF](http://www.sfm.state.or.us/CR2K_SubDB/MSDS/LIQUID_ENSYN_MNRP.PDF).
- \*\*\* European Biochar, 2016, Comparison of European Biochar Certificate version 4.8 and IBI Standards version 2.1. Available at: <http://www.european-biochar.org/biochar/media/doc/IBI-EBC.pdf>.
- \*\*\* IEA, 2016 Available at: [www.ieabioenergy.com](http://www.ieabioenergy.com).
- \*\*\* PYNE, 2016 Available at: <http://www.pyne.co.uk>.
- \*\*\* [www.thermalnet.co.uk](http://www.thermalnet.co.uk).

Received: 18 October 2016. Accepted: 29 November 2016. Published online: 30 December 2016.

Authors:

Cristina Șerbănescu, IPROCHIM S. A., 19-21 Mihai Eminescu Street, 010512 Bucharest, Romania, e-mail: [cristina.serbanescu@iprochim.ro](mailto:cristina.serbanescu@iprochim.ro)

Aurelia-Mihaela Oprescu, IPROCHIM S. A., 19-21 Mihai Eminescu Street, 010512 Bucharest, Romania, e-mail: [mihaela.oprescu@iprochim.ro](mailto:mihaela.oprescu@iprochim.ro)

This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

How to cite this article:

Șerbănescu C., Oprescu A. M., 2016 A short comparative review of commercial technologies for lignocellulosic biomass pyrolysis in Europe. *Ecoterra* 13(4):26-45.