Trends in Thermochemical conversion of waste and biomass

A brief overview

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***Abstract*— Energy and materials recovery from waste and use of residual biomass, such as agricultural waste, is today of significant importance to achieve a sustainable society, efficiently utilizing available natural resources. Although development of improved techniques for materials recovery there will be continues need for treatment of non-recyclable waste. Other important aspects are feasible techniques for local treatment of waste in regions with small communities and poor infrastructure as well as a need to for system facilitating multi-product production, especially in form of high value energy carriers and chemicals. There is waste number of thermochemical techniques for primary treatment of and further processing available, enabling different pathways to different end-user products. Nevertheless, these technologies are generally either developed for large-scale applications or not suitable for a waste feedstock, such as MSW or RDF. Trends in R&D to meet the societal needs are development of thermochemical waste conversion processes for diversified multi-product production, where different approaches are considered depending on feedstock type and plant scale. Also, small-scale units are today developed and commercial available.**

Keywords: Waste, MSW, Agricultural waste, thermochemical treatment

I. Introduction

Energy and materials recovery from waste and use of residual biomass, such as agricultural waste, is today of significant importance to achieve a sustainable society, efficiently utilizing available natural resources. For instance, it is very clear from the European strategy for waste management **Error! Reference source not found.** that the use of landfills must be residual and devoted to pre-treated wastes (not biologically active or not containing motile hazardous substances) to reduce the amount of waste for landfill. The focus should be re-use and recycling for effective material recovery is the general aim. For those streams of waste, including also residual streams from other treatment technologies, such as biological treatments, for which the material recovery is not effectively applicable, the energy recovery in form of thermal treatments should be provided. The forces towards this direction are basically the shortage of landfills and the stricter environmental legislations [2]. Worldwide around 2,000 conventional waste-to-energy (WtE) plants have been built, with a present throughput of more than 100 million tonnes of so-called municipal solid waste (MSW) per year. The main part of installations in operation today is equipped with suitable flue gas cleaning equipment and improved combustion control and thus easily complies with the strictest emission demands [1]. Nevertheless, the capacity is generally spread in the industrially developed countries, although also there unevenly distributed in relation to capacity needed, where infrastructure for transportation of feedstock and also efficient provision of energy in form of heat and power is in feasible. For the main part of the world there is significant lack of capacity for treatment of waste, including both materials as well as energy recovery. The society is also in many developing countries more spread out with people living in smaller communities with less developed societal infrastructure. Another important aspect is the desired energy product, where most of the world does not need heat but power and other high value energy carriers, such as liquid fuels or chemicals, todays WtE plants mainly produce heat and have a rather poor efficiency for power production. This implies a need for further development of commercial available thermal treatment technologies for diversified production of energy carriers, as exemplified in Fig. 1, at both smaller and larger scales.

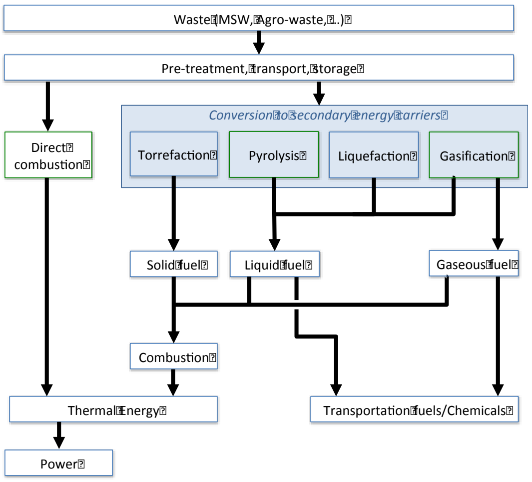

Fig. 1. A schematic of different possible paths for production of different energy carriers utilizing thermal conversion technologies. Adapted form [3].

The present paper will provide a general overview of conventional technologies, to provide an understanding of possibilities and limitations for development of new technologies, as well as technologies under development for thermochemical conversion of waste and biomass to different energy carriers. Waste and biomass considered will be MSW and sorted waste, so-called residual sorted waste (RDF), as well as biomass-derived waste from sources, such as agriculture. Since there are a vast number of different technologies at different stage of technology readiness level for the purpose, only a brief overview of selected technologies, indicated in green in Fig. 1, will be presented.

II. THE BASICS

A. Fuel properties

Waste and biomass is a diversified source and its diversity may be classified in a variety of ways depending on the origin and structure. One example is to divide into two groups as proposed by Basu [4]:

- Virgin biomass, including ligno-cellulosic biomass in form of wood, plants, and leaves; carbohydrate-based biomass such as crops and vegetables.
- Waste, including solid and liquid MSW, sewage, animal and human waste, gases derived from landfilling, as well as agricultural wastes.

The selection of a thermochemical conversion process depends on the characteristics of the feedstock used and desired end user product(s) [5]. In case of feedstock properties, the most important can roughly be divided as follows:

Physical properties: The physical properties of waste and biomass depend markedly on the type of feedstock. For instance, density may vary from 100 kg/m^3, for balsa, bagasse and straw, to 1200 kg/m^3, for lignum vitae [6]. Permeability to gas flow and thermal conductivity not only vary with type of feedstock shape and size, but also inside the feedstock species. Furthermore, all cereal straws resist compaction, which make them difficult to compress for economical transport and storage.

Thermodynamic properties: The thermodynamic property of waste and biomass plays a significant role in the thermal process. The conductivity also depends on factors such as moisture content, porosity and the present temperature. Other important properties are the specific heat, depending on the moisture content and the actual temperature, and the ignition temperature.

Chemical composition and energy content: Many organic compounds in waste and biomass contain oxygen, but the degree of oxidation varies. The quantities of cellulose, hemicellulose and lignin vary between different types of biomass plants. Each of these components has there own pyrolysis chemistry in thermo-chemical conversion, and therefore the composition of the volatilized intermediary compounds can vary substantially depending on waste and biomass used [7]. The energy content varies between different biomass fuels as exemplified in TABLE I. displaying the composition and energy content for some typical feedstocks.

TABLE I. EXAMPLES OF FEEDSTOCK COMPOSTIONS AND PROPERTIES (AS RECEIVED) **ERROR! REFERENCE SOURCE NOT FOUND.**

	Oat straw	**RDF I**	**RDF II**	**MSW**
Proximate analysis (wt%)				
Moisture content	8.20	4.24	21.90	6.16
Ash content	5.42	25.02	8.90	15.78
Volatile matter	73.9	70.29	51.60	68.13
Fixed carbon	12.48	0.45	17.60	9.93
Ultimate analysis (wt%)				
Carbon	42.35	38.02	35.43	46.2
Hydrogen	5.16	5.53	4.64	7.65
Nitrogen	0.45	0.77	0.69	1.71
Sulfur	0.07	0.34	0.42	0.23
Oxygen	38.7	26.09	28.0	22.27
Total (with halides)	100.0	100.0	100.0	100.0
Calorific values (MJ/kg)				
Net calorific value (LHV)	16.02	13.5	14.0	17.4
Gross calorific value (HHV)	17.39	14.8	15.55	19.22

In case of waste, is it important to note that solid-waste characteristics differ considerably among communities and nations as well as may also vary considerably during a season. When consider any waste to energy recovery project it is therefore central to have accurate data on the future waste quantities and characteristics that form the basis for the design of the thermochemical conversion system. In particular, the energy content (calorific value) must be above a minimum level. Also, the specific composition of the waste is also important. An extreme waste composition of only sand and plastics is not suitable for incineration, even though the average energy content is relatively high.

B. Thermochemical conversion

1) Fundamentals

Thermal conversion of a fuel, such as organic waste and biomass, consists of a sequence of pyrolysis, gasification and/or combustion steps. Within a conventional energy recovery combustion system, these three steps are integrated, whereas in the case of alternative conversion systems, intermediate energy carriers may be generated and used in combustion step or for other purposed such as upgrading to chemicals or transportation fuels, as previously indicated in Fig. 1. Fig. 2 presents a principal overview of the steps and chemical processes during thermochemical conversion. It shows that any thermal treatment begins with a pyrolysis process. If heat and steam or in limited amounts air is added then gasification occurs. If excess amount of air is added complete combustion will take place. In most cases, heat to sustain the thermal process is provided by the internal combustion process, so-called direct heating, but for some technologies heat can be provided from an external source, so-called indirect heating.

Pyrolysis: Pyrolysis is the thermochemical decomposition of organic matter in the absence of an oxidizing agent, producing char, pyrolysis oil and pyrolysis gas. The quality and relative proportion of the products depend on several factors such as temperature, heating rate, vapors residence time, pressure, biomass composition, etc. Pyrolysis generally starts at

300 °C and continues up to 600–700 °C, limits that are not absolute. Generally, lower process temperature and long vapor residence time favor char production, whereas high temperature and long vapor residence time increase the gas yield. Moderate temperature and short vapor residence time favor production of liquids [9].

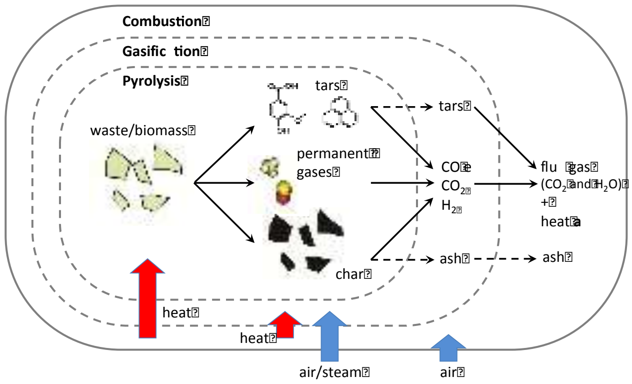

Fig. 2. A schematic of steps and chemical processes. Adapted from [5].

Gasification: A fuel gas can be produced from biomass or other feed stocks by partial oxidation at high temperature using oxidizing agents such as air, oxygen, steam, carbon dioxide or combination of these. In general air is used as oxidaizing agent for heat and power applications and oxygen/steam for syngas applications, where nitrogen dilution is a problem. In case of biomass gasification, the temperatures used are typically between 500 and 1600 °C [10]. There are a number of chemical reactions occurring during the conversion, including the pyrolysis step, gasification of the char and decomposition of the tars formed. Of significant importance is the tar produced, present in different amounts, depending on the gasifier technology, feedstock used and process conditions [11].

Combustion: This implies complete oxidation at high temperature using air as oxidizing agent. Also in this case there is a large number of reactions, including also the pyrolysis and gasification. The complete process can be carried out in one well-mixed reaction zone or in subsequent steps where the oxidizing agent is introduced stepwise, optimizing the combustion and thus minimizing undesired impurities in the flue gas.

The different products and sidestreams produced in the different thermochemical processes using waste and biomass are presented in TABLE II. All thermochemical conversion processes, different impurities need to be removed to a certain degree, depending on the requirements in the final utilization. For gasification and combustion most of the impurities are present in the product and flue gas produced, respectively, and in the ash. In case of pyrolysis, the impurities are more disparately distributed among the three products: char, pyrolysis oil and pyrolysis gas. The distribution depends on the pyrolysis process and conditions utilized for the conversion.

TABLE II. PRODUCTS AND SIDESTREAM PRODUCED IN DIFFERENT THERMOCHEMICAL PROCESSES

Pyrolysis [12]	**Gasification [11]**	**Combustion [13]**
Pyrolysis oil Acids, sugars, aldehydes, esters, alcohols, ketones, phenolics, oxygenates, Hydrocarbons, steroids ***Permanent gases*** CO, CO_2, H_2O, H_2, CH_4, hydrocarbons (C2–C5) ***Char*** Inorganics, unconverted organic solids and carbonaceous residues	***Permanent gases*** CO, CO_2, H_2O, H_2, CH_4, hydrocarbons (C2–C5) ***Condensable compounds*** Tars ***Ash*** Particle inorganics, including heavy metals ***Impurities*** H_2S, CS_2, COS, AsH_3, PH_3, HCl, NH_3, HCN, and alkali salts,	***Flue gas*** CO_2, H_2O ***Ash*** Particle inorganics ***Impurities*** HCl, HF, SO_X, NO_X, dioxine, heavy metals

III. THERMOCHEMICAL CONVERSION SYSTEMS

Flexible utilization of waste and biomass to useful energy carriers by means of thermochemical conversion is carried out in more or less complex systems, including beside the thermal conversion a variety of upstream and downstream process components, selected depending on the requirement of the end user utilization and feedstock properties. Examples of components in thermochemical conversion systems are illustrated in Fig. 3. In the present paper

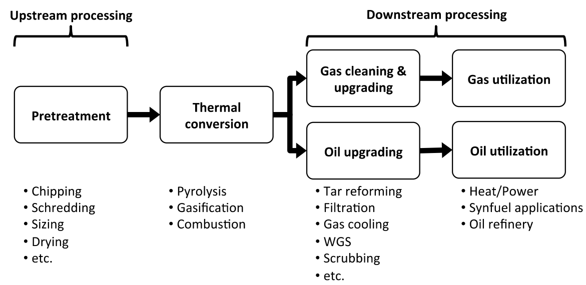

Fig. 3. A schematic of components in a thermochemical conversion system.

A. *Upstream processing*

There are a number of different techniques, including e.g. sorting, chipping, shredding, drying, pelletizing, sizing, available commercially. In cost efficient systems you always try to minimize the need for pretreatment since many of the techniques are quite energy intensive and thus costly.

B. *Thermal conversion technologies*

There are a vast number of different designs of thermal conversion concepts applied to different types of feedstock. In principle can all concepts be used for the pyrolysis, gasification and combustion, but not all are suited for all types of waste and biomass. The most commonly used concepts are grate-furnace, fluidized beds, fixed bed and rotary kilns. Three of these concepts are exemplified in Fig. 4 and briefly described below. An example of a rotary kiln pyrolysis application is shown in Fig. 7.

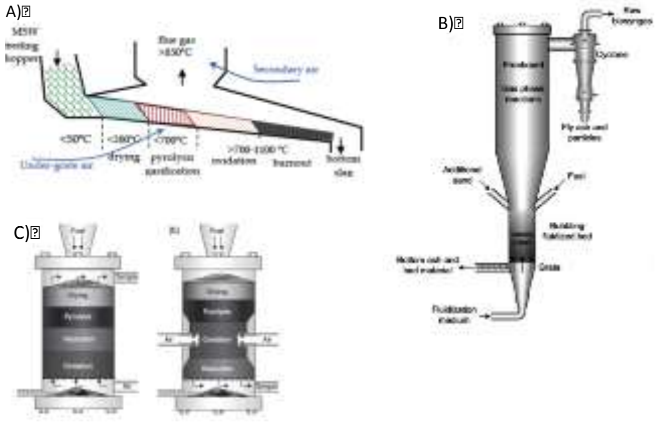

Fig. 4. Most common technologies for thermochemical conversion of waste and biomass. A) Grate, B) Fluidized bed, C) Fixed bed [5], [14]

Grate furnaces (Scale > 10 MW_{fuel}): Over 90 % of waste fired facilities in Europe operate with grate furnaces [14]. The function of the grate is to transport, mix and distribute, loosen, and position the material in the furnace to the combustion zone [15]. There are various types of moving grate designs (e.g., rocking grates, reciprocating grates, traveling grates, roller grates, and cooled grates), which vary in design of how the waste is conveyed through the furnace. The constant movement of the bars in the grate system ensures a good mixing profile, which ensures a rapid drying of the waste. In addition, it also provides a good control over the flame position in the furnace, which prevents hot spots from occurring. Furthermore, the moving grate enables a high quality or complete burn out of the bottom ash before falling down through the bottom ash discharger. The primary combustion of the waste occurs in the furnace, the chamber over the grate, and the secondary combustion occurs in the upper afterburning chamber. In these two parts, especially the afterburning chamber, it is important that the gases experience sufficient long retention time at high temperatures of 850 °C to ensure a good combustion and for all the reaction to occur in the flue gas before entering the boiler [15].

Fluidized beds (Scale > 10 MW_{fuel}) Fluidized beds contains a suspended bed of inert material (e.g., silica or olivine sand) with an approximated particle diameter of 0.5-3 mm [15], creating high turbulence flows and very efficient heat distribution over the whole system, resulting in very efficient heat- and mass transfers, and stable operation [10]. The bed material can also be a catalytically active material, such as dolomite, promoting in bed tar reduction, or a material enabling absorption of impurities such as sulfur, chlorine etc [11]. Waste and biomass is continuously fed into the bed, either from the side or from the top. The feedstock is crushed, mixed, dried, and partially combusted in the bed. The section above the bed is called freeboard, and is much longer than the fluidized bed section in order to provide long enough retention time for all the reactions to occur. Fluidized beds can be divided into three main types, bubbling fluidized bed (BFB), circulating, fluidized bed (CFB), and rotating fluidized bed (RFB). BFB combustors are very common for treatment of sewage sludge and other industrial sludge [15]. The bubbling fluidized beds operate at relatively low gas velocities, typically below 1 m/s. In the BFB gasifier most of the conversion of the feedstock to product gas takes place in the dense bed region in the bottom of the gasifier, even though some conversion continues in the freeboard section. The circulating fluidized beds operate at much higher gas velocities, 3–10 m/s, and are significantly different in their hydrodynamics, compared to a BFB reactor. The solids are dispersed all over the tall riser, allowing for a long residence time for both the gas and the fine particles. In the CFBG, the particles are separated from the gas in a cyclone and recycled back to the bottom of the reactor. [5]

Fixed bed (Scale: 10 kW_{fuel} – 10 MW_{fuel}): In a fixed bed gasifier, the fuel is supported on a grate where the fuel moves down in the reactor as a plug. This type of gasifier is generally suitable for small-scale operation. There are three main types of fixed bed gasifier technologies: updraft, downdraft and cross-draft. The two first are shown in Fig. 4 C). Depending on the gasifier type the feedstock slowly flows passes sequentially through the different zones of drying, pyrolysis, gasification (reduction) and combustion zones by gravity. Ashes are removed by an ash discharge system at the bottom of the gasifier. The product gas is either collected in the top (updraft) or in the bottom (downdraft). In case of the updraft gasifier, the product gas contains a significant proportion of tars and hydrocarbons, and these contribute to the relatively high heating value of the gas. The product gas requires substantial clean up if further processing of the product gas is to be performed. In the downdraft gasifier the converted gas passes through the high temperature in the oxidation zone, decomposing the tar compounds, producing a product gas with relatively low tar content. However, downdraft gasifiers have an upper size limit of 1-2 MW_{fuel}, limiting their usefulness for handling larger amount of waste and biomass. [5]

1) Downstream processing and applications

The different products formed in the thermal conversion step are more or less contaminated depending on the process and the feedstock. Depending on the utilization, there is a general need for cleaning and upgrading of the raw gaseous and liquid products to prevent eventual problems, such as plugging, erosion, corrosion, catalyst poisoning, storage problems, in downstream processing, but also to prevent pollution of the environment. The needs for cleaning and upgrading are different for the three types of thermochemical conversion processes, but also the maturity of possible technologies to be applied. Direct combustion is the most mature in terms of commercial use; especially for large-scale systems, and in case of gasification and pyrolysis it is generally dependent on preferred utilization of products, where there is a sliding scale from research to commercial use.

As pointed out above down stream processing is generally directly related to product utilization and also the major part of a plant in terms of process equipment and thus also a major part of the total investment costs. It is therefore practical to present downstream processing in perspective of an overall application.

a) Direct combustion

The selected thermal treatment technology for power production should have a net efficiency. When reviewing the efficiency, the entire conversion process starting at the waste-tipping floor to the electrical power delivered by the generator, should be considered. Common net efficiencies are 18 - 27% for a normal installations running up to 32% for high efficiency installations. A small scale, multi stage process operating at similar temperatures and pressures can at best match that efficiency. Fig. 5 shows a process layout of a modern large-scale waste to energy plant.

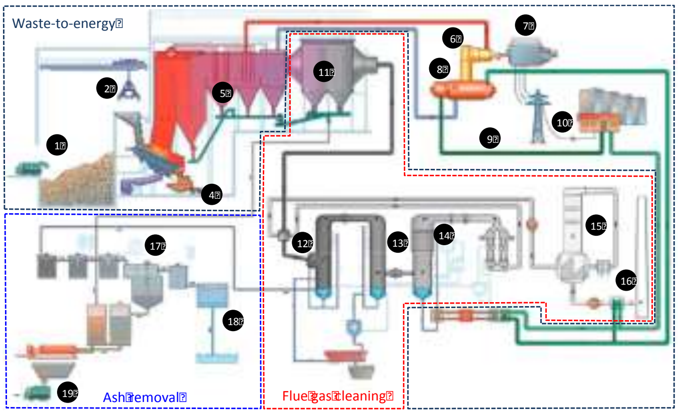

Fig. 5. Example of a modern waste to energy plant. [16] 1. Waste bunker; 2. Fuel feeding; 3. Furnace, 1000 °C; 4. Slag to water filled trough; 5. Heat exchangers, steam data typically T = 400 °C, P = 40 bar; 6. Steam turbine; 7. Generator; 8. Heat exchanger district heating; 9. District heating (T = 70 – 120 °C); 10. Electricity; 11. Electrostatic precipitator; 12-13. Water scrubbing; 14. Condensor, heat pump extracting heat; 15. SCR catalytic convertor for NOx; 16. Chimney; 17. Cleaning of scrubber water; 18. pH adjustment and release of water; 19. Sludge and fly ash is stored

The plant includes many process units, as described in the figure, which can be grouped as follows:

a) Waste to energy: After the waste bunker, cranes feed the waste into the hopper. The waste proceeds down the feeding chute, preventing cold air from entering the system, as temporary storage and as a safety against backfire. The waste is then fed onto the grate unit by a push principle, operated by hydraulic cylinders. The thermal treatment step is designed to hinder the formation of pollutants, especially NOx, and organic compositions such as dioxins. Appropriate measures to ensure an efficient combustion process (complete burnout of the bottom ashes and the flue gases, low dust content in the raw flue gas) comprise a long flue gas retention time at high temperature with an appropriate oxygen content, intensive mixing and recirculation of flue gases, optimal supply of combustion air below the grate and before inlet to the after-combustion chamber, and proper mixing and agitation of the feedstock on the grate. The heat in the flue gas is subsequently recovered stepwise in heat exchangers to produce steam with sufficient steam data (typically 400, P = 40 bar for power generation in a steam turbine. Residual heat may also be recovered for district heating or other low heat applications if desired and a heat sink is available, increasing the overall efficiency. [17]

b) Flue gas cleaning: The main pollutants that need to be treated are, fly ash, including heavy metals, acids and acid precursors (e.g., SO_X, NO_X, HCl, HF), and dioxins [14], [18]. Since combustion of waste and biomass is a mature technology, commercial techniques for handling potential impurities or pollutants present in the flue gas are available today. A few examples are shown in TABLE III. However, implementation of existing techniques is in many cases, as for gasification, a matter of scale and feedstock resources availability. Cost efficient systems large-scale plants are most readily implemented in regions with rich supply of feedstock and where provision for both heat and power is possible.

TABLE III. POLLUTANTS TREATED IN DIFFERENT PROCESS UNITS [14]

Pollutant	Process technology
Fly ash	Electrostatic precipitator and fabric filter
Heavy metals	Electrostatic precipitator and dry scrubber
SO_X	Wet scrubber or dry cyclone
NO_X	Selective catalytic or non-catalytic reduction
HCl and HF	Wet or semi-dry scrubber
Dioxins	Activated carbon and fabric filter

c) Ash removal: Any thermal treatment of a solid feedstock generates a large amount of solid residues at different locations throughout the process, which can be divided into three main categories, furnace bottom ash, fly ash, and other air pollution control residues [19]. The differences between the ash categories are mainly the size and metal content. The initial quality of the feedstock has a significant effect on the quality of the residues [20]. The ash is today generally sent for landfill but recent development is directed toward processes for metal recovery.

b) Gasification

Fig. 6 shows the 28 MW_{th} CHP plant in Skive, Denmark, based on BFB biomass gasification, producing power and district heat of 5.5 and 11.5 (95/50 °C), respectively. Also for this application, the plant can be divided into three parts: a) thermochemical conversion of the solid fuel, b) gas cleaning and upgrading and c) the power and heat generation, including also flue gas cleaning after the combustion in the boiler and the engines.

a) BFB thermochemical conversion: The gasifier is basically a cylindrical steel vessel with a layer refractory lining equipped with a cyclone to return eventual entrained ash, bed material or char to the gasifier. The gasifier is be fed with 110 tpd of wood pellets biomass by using through live bottom-type hoppers of special design and metered by a screw conveyer system. The fluidizing gasifying media is air, introduced into the reactor through a special gas distributor. In principle, oxygen and steam could also be used. Secondary air may be introduced into the freeboard to control the temperature and enhance tar cracking. The dolomite bed material used promotes tar reduction.

b) Gas cleaning and upgrading: In the example in Fig. 6 the first step is a tar reformer followed by a filter for particle removal and a scrubber to remove inorganic impurities.

Of significant importance for most biomass gasification systems is the tar produced, present in different amounts, depending on the gasifier technique, feedstock used and process conditions. The tars may cause clogging of piping and blocking catalyst surface downstream the gasifier [5]. Removal or conversion of tar is more important when the product gas is intended for syngas applications. In case of heat and power applications, the tar compounds can in most cases be combusted directly. Two basic approaches used to remove tars from the product gas stream, physical methods or thermochemical methods. In physical methods condensed tar aerosols are removed using technologies similar to those used for particulate removal such as wet scrubbers, electrostatic precipitators, or other technologies. These require that the product gas be cooled to ensure the tars are in a condensed form. A major challenge is to recover the energy stored in the tars utilizing these technologies. Thermochemical methods can be divided into thermal methods, implying decomposition at high temperatures, generally above 1100 °C, and catalytic tar reduction methods, applying a catalyst at temperatures 850-950 °C, similar as for the gasification conditions. Both these methods convert the tar to permanent molecules. The use of a catalytic approach is more feasible due to the lower temperature and also since possible addition of steam in catalytic steam reforming promotes hydrogen formation of importance for syngas applications. A major challenge in recent years have been the need for removal of ash particulates and alkali salts prior to the catalytic reactor, imposing a heat efficiency problem, since the particle separation need to be performed at much lower temperature than present in the gasifier and the catalytic reactor. Nevertheless, recent development of catalyst for so-called high dust load catalytic tar reduction is today used commercially as shown in Fig. 6.

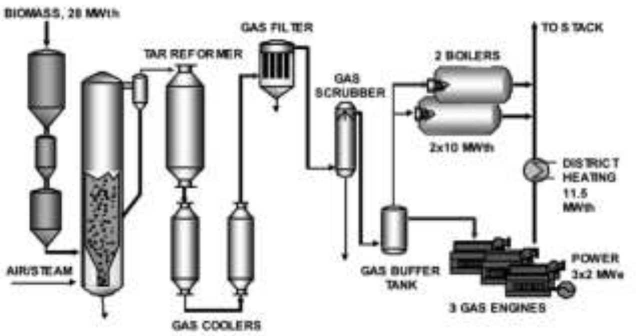

Fig. 6. Simplified scheme of the Andritz Carbona Low-Pressure Bubbling Fluidized Bed gasification process. [5]

Cost efficient removal of impurities in form of ash and char particulates, tar, and inorganic impurities, such as H_2S, CS_2, COS, AsH_3, PH_3, HCl, NH_3, HCN, and alkali salts is the major barrier for commercially utilizing the product gas, especially when syngas applications are considered. Since most gas cleaning and upgrading process equipment is developed for large-scale processes, commercialisation is impeded by feedstock supplying issues for large-scale applications or cost implementation of cost efficient systems at smaller scale. [21]

b) Power and heat generation: Electric power is produced by combusting the produced gas in gas engines connected to generators and heat by heat exchanging the flue gas from the engines or by combustion of the gas in separate boilers.

c) Pyrolysis

There are a number of pyrolysis plants in operation in Japan [22] for pyrolysis of waste. Fig. 7 shows an example of a pyrolysis plant, the Yame Seibu plant, based on the Mitsue R21 process. MSW is pyrolized in a rotary drum at 450 °C, producing an oil rich pyrolysis gas, char as well as ferrous and nonferrous metals. The pyrolysis gas is directly combusted in a high temperature combustor connected to a boiler producing steam for power generation. Residual ash is in form of fused ashes sent to landfill. Particulates and impurities in the flue gas are removed in two bag filters in series, where the first collects the particulates and the second is for acid gas control by injection of lime.

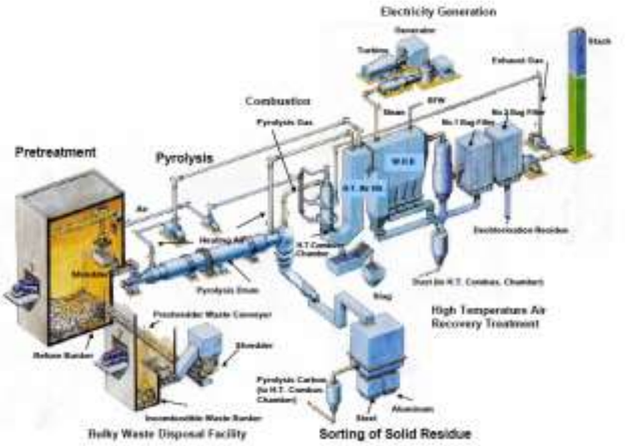

Fig. 7. An example of pyrolysis plant, Yame Seibu Plant, Japan, for waste [22].

The most significant challenge is the general instability of the produced pyrolysis oil, caused by the oxygen content, usually greater than 35 % in more than 300 different compounds in case of biomass as a feedstock [23]. The oxygen causes a further polymerization of the oil to larger polymer chains with high viscosity. Another problem is the high content of water may cause phase separation and handling problems if exceeding a threshold [24]. Both the polymerization and phase separation are relatively rapid processes, changing the oil composition often in less than a day, making it difficult to store and transport the produced oil. At present, there is no commercially viable technical solution to handle these problems, pushing an immediate utilization of the produced biomass pyrolysis oil in refinery and distributed pyrolysis oil applications.

IV. Trends

A. Diversified recovery

Flexible production of diversified energy carrier products from waste resources is an attractive solution to enable adaption to different needs maximizing also cost efficiency. Fig. 8 shows a possible schematic process flow diagram of a possible process for producing multiple products from the intermediate energy carriers; char, pyrolysis oil and syngas. The process also includes recovery of inorganics with a feasible utilization as fertilizers. There are of course many different technology pathways for achieving a flexible process. Two technology examples will be considered below.

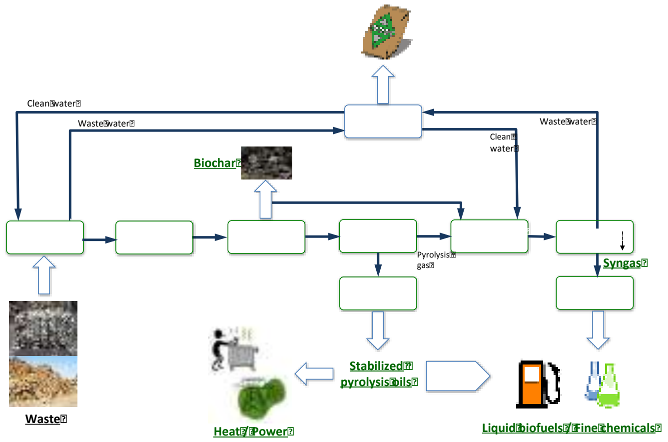

Fig. 8. A schematic process flow chart of a possible process for diversified production of different energy carriers.

1) The WoodRoll® process

An interesting technology under development suitable for adapting to flexible is the WoodRoll® thermal gasification technology for biomass gasification, under development by Cortus Energy in Sweden. The WoodRoll® technology is an integrated process for converting wet solid woody biomass to clean syngas in three steps, drying, pyrolysis and gasification, as some of the modules also included in Fig. 8. The process is fully allothermal from wet biomass to clean syngas and the main process equipment and functionality is explained as follows: 1) A indirectly heated rotating drum dryer, where the biomass is dried to a moisture content below 5 wt%. 2) A pyrolysis reactor of a similar type as the dryer. The oil rich pyrolysis gas is combusted in radiation tube burners, located on top of the gasifier. The produced biochar is conveyed and milled before entering the gasifier. 3) The gasifier is an entrained flow gasifier indirectly heated by the radiation tube burners. The reaction and conversion of the finely milled biochar with superheated steam at the high operation temperatures of approx. 1100 °C is rapid and complete. The high temperature enables tar destruction Residual heat from the gasification process supplies heat to the dryer and pyrolysis reactor in order to keep high efficiency within the system. The process configuration allows for a thermal yield of 80 % starting from wet biomass producing a relatively clean product gas. [25]

By exploiting the modular configuration of the WoodRoll® technology, adding inventive modules, a new flexible process for diversified production of the intermediary products biochar, stabilized pyrolysis oils and syngas, further upgraded high value advanced biofuels, can be achieved, as the one shown in Fig. 8. In this proposed process concept there are four main parts, at present under development, to be demonstrated before a commercially viable process for waste and agro-waste feedstock:

- Leaching pretreatment technology to separate impurities from the feedstock, enabling the use of feedstock with high ash content as well as reducing the need for downstream gas cleaning.
- Recovery of the impurities in a separation step to produce e.g. fertilizer.
- Fractional condensation of the pyrolysis oil separating the light oil fraction from oligomeric products, acids and water to minimize the risks for phase separation.
- Upgrading of the light and heavy oil fraction by hydrotreatment and hydrocracking, respectively, to produce stable oils and liquid biofuels. The total concept is interesting and the main parts are under development by independent research groups

The technologies are under development by different research groups in the industry, academia and institutes. Plans for demonstrating the technologies in a complete system is under preparation to be accomplished in next forthcoming years.

2) Plasma pyrolysis and gasification

Application of plasma-based systems for waste management is a relatively new concept. A plasma thermochemical process is a feedstock treatment technology that uses electrical energy and the high temperatures (> 2000°C) created by an electric arc gasifier. The arc decomposes the organic parts of the feedstock primarily into an elemental product gas and a char in case of pyrolysis. Plasma is used most efficiently either in a pyrolysis mode or a pure oxygen gasification mode. The plasma arc has very high electrical energy consumption and if oxygen is used for the plasma gasification, also the oxygen use for the gasification will contribute towards internal energy use. A clear advantage of plasma is that the plasma effectively produces a relatively clean product gas without any remaining tar. Principal advantages that plasma offers to waste treatment processes have been summarized by Heberlein [26]:

- High energy densities and high temperatures allows for:
  - rapid heating and reactor start-up,
  - high heat and reactant transfer rates,
  - smaller installation size for a given feedstock throughput,
  - melting of high temperature materials.
- Use of electricity as the energy source results in:
  - decoupling of the heat generation from the oxygen potential and the mass flow rate of the oxidant or air, increasing process controllability and flexibility,
  - lower off-gas flow rates and consequently lower gas cleaning costs,
  - the possibility of producing valuable (saleable) co-products

Although important progress in plasma pyrolysis in recent years, commercial application of plasma pyrolysis technologies for treating *solid* waste streams, especially for MSW, are generally limited. Nevertheless, plasma pyrolysis of hazardous *liquids and gases* is becoming increasingly important and is already a commercially proven technology [27]. Also, relatively small-scale plasma pyrolysis installations for treatment of polymers [27], medical waste [29] and low-level radioactive waste [30] do exist.

Plasma gasification and vitrification, a technology being discussed in the next subsection, seems to be preferred over plasma pyrolysis for this type of waste streams. The high temperature conditions in plasma gasification together with addition of oxygen result in a complete decomposition of organic compounds into their elemental constituents, forming a high-energy product gas, consisting mainly of H_2 and CO and no hydrocarbons. The inorganic fraction (glass, metals, silicates, heavy metals) is melted and converted into a dense, inert, non-leaching vitrified slag, easily stored in landfill or possibly used as building material. After removal of inorganic impurities and upgrading the syngas can be used for production of power and/or heat, or second generation liquid (bio)fuels. [31] A commercial example of plasma gasification technology, developed by Westinghouse Plasma Corp., owned by Alter NRG Corp., is shown in Fig. 9 [32]. The plasma reactor is a plasma-fired furnace, containing the waste and coke (about 4 wt% of the total charge). Plasma heating of a fraction of the air reduces the amount of coke and air needed to generate the high temperatures in the furnace. The waste composition determines how much incoming air needs to be heated by the plasma. The vitrified slag is exiting thin the bottom of the reactor. The product gas, exits the top of the reactor, and is cooled and going through a series of conventional cleaning, such as wet electrostatic precipitator, polishing scrubber and sulfur hydrolysis, and upgrading steps before utilized. There are a number of installed facilities, based on the technology, such as Mihama-Mikata plant in Japan (WtE of 22 tons/day) [33] and Utashinai, Japan (WtE 165 tons/day) [34]. However, the recent large-scale project building the two WtE plants in Tee Valley, UK (50 MW electricity, 350 ktons/year non-recyclable waste electricity per plant) have been halted after completing one of the plants due to technical problem during commissioning [35]. Some claim that a too large jump was possibly taken in the scale up of the technology. What this unsuccessful project will mean for the future development is to be discovered.

Fig. 9. Schematics of the Westinghouse Plasma Technology [32].

B. Small scale WtE

Small-scale WtE plants, in comparison to the traditional mass burn incinerators that are generally used at the moment; this type of facility will have a very small footprint and can therefore be built in urban areas without looking out of place. Waste treatment can then be addressed at a local level, close to the waste source, rather than spending money on transporting waste around the country to landfill sites – an activity, in itself, creating more traffic congestion and produces even more greenhouse gases. This type of plant should enable production of power and/or other energy carriers, sometimes also be mobile to allow for use at the site where the feedstock is available. Since conventional combustion technology relies on steam turbines for power production this is generally not a feasible option. Therefore, on-going R&D activities generally focus on utilizing pyrolysis and gasification for this purposes. Fig. 10 shows a schematics of an example of the small-scale biomass gasification technology BioMax®100 Gen2 Modular Biopower System developed by Community Power Corporation, US. [36] The system includes a downdraft gasifier a simplified gas cleaning in form of a filter for particulate removal. The produced product gas or fuel gas for different end-user applications, including electrical power only, combined heat and power (CHP), gas production only (boilers and dryers), mechanical shaft power and cooling.

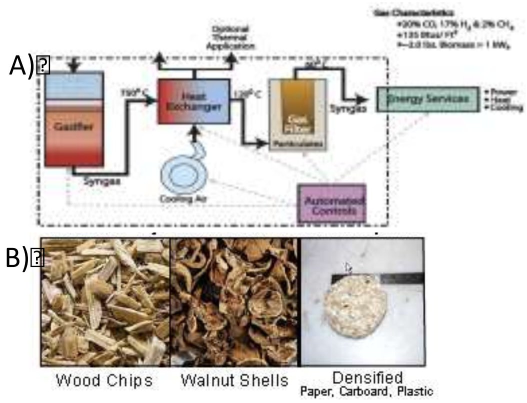

Fig. 10. A module process flow diagram of the BioMax®100 Gen2 **Error! Reference source not found.**.

V. SUMMARY

Thermochemical conversion technology has been around for a long time but still large efforts are made to develop new techniques for treatment of waste and other residual materials. A major driving force is the continue need for treatment of non-recyclable waste, regardless of development of new methods for recycling and new materials with improved recyclability. Other important aspects are feasible techniques for local treatment of waste in regions with small communities and poor infrastructure as well as a need to for system facilitating multi-product production, especially in form of high value energy carriers and chemicals. There is waste number of thermochemical techniques for primary treatment of and further processing available, enabling different pathways to different end-user products. Nevertheless, these technologies are generally either developed for large-scale applications or not suitable for a waste feedstock, such as MSW or RDF. Trends in R&D to meet the societal needs are development of thermochemical waste conversion processes for diversified multi-product production, where different approaches are considered depending on feedstock type and plant scale. Also, small-scale units are today developed and commercial available.

REFERENCES

[1] DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. Accessed September 2016: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098

[2] J. Loenicker. (2013) ecoprog, Waste to Energy 2012/2013 – The World Market for Waste Incineration Plants. [Online]. http://www.ecoprog.com/en/publications/energy-industry/waste-to-energy.htm

[3] L. Helsen1, and A. Bosmans, "Waste-to-Energy through thermochemical processes: matching waste with process," 1st Int. Symposium on Enhanced Landfill Mining, Belgium 4-6 October, 2010.

[4] P. Basu, Biomass gasification and pyrolysis: practical design and theory. Academic Press, Burlington, USA, 2010.

[5] K. Engvall, T Liliedahl, and E. Dahlquist, Biomass and black liquor gasification, Chp. 6 in Technologies fo converting biomass to useful energy. CRC Press, Taylor & Francis Group, London, UK, 2013.

[6] C. Di Blasi, "Influences of physical properties on biomass devolatilization characteristics," Fuel, vol. 76(10), pp. 957–964, 1997.

[7] D. Mohan, C.U. Pittman Jr., and P.H. Steele, "Pyrolysis of wood/biomass for bio-oil: a critical review," Energy Fuels, vol. 20, pp. 848–889, 2006.

[8] Phyllis: Database for biomass and waste. Version: 4.13. Energy Research Centre of the Netherlands ECN-Biomass, http://www.ecn.nl/phyllis. Accessed September 2016.

[9] A.V. Bridgwater, "Catalysis in thermal biomass conversion," Appl. Catal. A: General, vol. 116, pp. 5–47, 1994.

[10] A. Umberto Arena, "Process and technological aspects of municipal solid waste gasification. A review," Waste Management, vol. 32, pp. 625-639, 2012.

[11] K. Engvall, H. Kusar, Sjöström, and L.J. Pettersson, "Upgrading of raw gas from biomass and waste gasification: challenges and opportunitie," Top. Catal. Vol. 54, pp. 949–959, 2011.

[12] T. Bridgwater, "Fast pyrolysis based biorefineries," ACS Meeting, Washington, 2005.

[13] The World Bank, "Municipal Solid Waste Incineration", World bank technical guidance report, 1999.

[14] M.J. Quina, J.C.M. Bordado, and R.M. Quinta-Ferreira, "Air Pollution Control in Municipal Solid Waste Incinerators, The Impact of Air Pollution on Health, Economy, Environment and Agricultural Sources,", ISBN: 978-953-307-528-0 , 2011.

[15] European Comission, Integrated Pollution Prevention and Control, August 2006, Found online September 2016: (http://eippcb.jrc.es/reference/wi.html).

[16] Lars Jacobsson SYSAV, Panndagarna 2011. Accessed September 2016: http://u1715295.fsdata.se/wp-content/uploads/2013/11/Panndagarna2011_Lars_Jacobsson.pdf

[17] N. Popara and D. Kyriakidou, "Solid residues from Swedish WtE plants-a hazardous waset or a potential income?", Master thesis, KTH, 2013.

[18] J. Vehlow, B. Bergfeldt, C. Wilén, J. Ranta, H. Schwaiger, H.J.M. Visser, S. Gu, E. Gyftopoulou, and J. Brammer "Management of Solid Residues in Waste-to-Energy and Biomass Systems ," Institut für Technische Chemie , Karlsruhe, ISSN 0947-8620 , 2007.

[19] L Sivula, "Characterisation and treatment of waste incineration bottom ash and leachate," Doctoral thesis, University of Jyväskylä, Finland 2012, ISBN 978-951-39-4656-2.

[20] Stantec Consulting Ltd. and Ramboll Denmark, "Waste to Energy: A Technical Review of Municipal Solid Waste Thermal Treatment Practive," Burnaby, BC, Final Report Project No.: 1231-10166, 2011.

[21] Knoef, H.A.M.: Practical aspects of biomass gasification. In: H.A.M. Knoef (ed): Handbook of biomass gasification. BTG Biomass Technology Group BV, Enschede, The Netherlands, 2005.

[22] IEA Bioenergy Task 32: (Accessed September 2016) http://www.ieabcc.nl/workshops/Tokyo_Joint_Meeting/02_Mitsui.pdf

[23] Q. Zhang, J. Chang, T. Wang, and Y. Xu, "Review of biomass pyrolysis oil properties and upgrading research," Energy Conver. Manage., vol. 48, pp. 87–92, 2007.

[24] A. Oasmaa and C. Peacocke, Properties and fuel use of biomass derived fast pyrolysis liquids, a guide, VTT, Espoo, 2010.

[25] M. Amovic, P. Donaj, B. Moner, R. Alzuheri, and R. Ljunggren, " Fuel testing procedure for pyrolysis and gasification of biomass using TGA and WoodRoll", SGC Rapport 2014:289.

[26] J. Heberlein, "Generation of thermal and pseudothermal plasmas", Pure Appl. Chem., 64 (5), pp. 629, 1992.

[27] J. Heberlein and A.B. Murphy, "Thermal plasma waste treatment", J. Phys. D: Appl. Phys, vol. 41(5), pp. 053001 2008.

[28] R.R. Guddeti, R. Knight, and E.D. Grossmann, "Depolymerization of polyethylene using induction-coupled plasma technology", Plasma Chemistry and Plasma Processing, vol. 20(1), pp. 37–64 2000.

[29] S.K. Nema and K.S. Ganeshprasad, "Plasma pyrolysis of medical waste", Current Science, vol. 83(3), pp. 271–278, 2002.

[30] High Temperature Technologies Corp. (HTTC, Canada), "Plasma Furnace for the treatment and disposal of Solid Toxic and Low-Level Radioactive Waste", Accessed September 2010, from http://www.httcanada.com/chemtoxrad.html

[31] T. Malkow, "Novel energy and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal", Waste Manag., vol. 24(1), pp. 53–79, 2004.

[32] Plasma. Accessed September 2016: http://www.alternrg.com/wp-content/uploads/2012/12/43FLDR011_Gasificatn-en.pdf

[33] Gasification and Syngas Technologies Council (GSTC). Accessed September 2016: http://www.gasification-syngas.org/resources/world-gasification-database/mihama-mikata-waste-gasification-plant

[34] K.P. Willis, S. Osada, and K.L. Willerton, "Plasma gasification: Lessons learned at Ecovalley WtE facility", Proceedings of the 18th Annual North American Waste-to-Energy Conference NAWTEC18 May 11-13, 2010, Orlando, Florida, USA.

[35] M. Clay, "Up in the air", Recycling & Wase World, 27 May 2016.

[36] BiomMax® overview. Accessed September 2016: http://www.gocpc.com/more-information/biomax-overview.html