# Waste to power

MILOUD OUADI, JOHN BRAMMER, ANDREAS HORNUNG, AND MARTIN KAY

**ABSTRACT:** There has been a growing trend towards the use of biomass as a primary energy source, which now contributes over 54% of the European pulp and paper industry energy needs [1]. The remaining part comes from natural gas, which to a large extent serves as the major source of energy for numerous recovered fiber paper mills located in regions with limited available forest resources. The cost of producing electricity to drive paper machinery and generate heat for steam is increasing as world demand for fossil fuels increases. Additionally, recovered fiber paper mills are also significant producers of fibrous sludge and reject waste material that can contain high amounts of useful energy.

Currently, a majority of these waste fractions is disposed of by landspreading, incineration, or landfill. Paper mills must also pay a gate fee to process their waste streams in this way and the result of this is a further increase in operating costs. This work has developed methods to utilize the waste fractions produced at recovered fiber paper mills for the onsite production of combined heat and power (CHP) using advanced thermal conversion methods (pyrolysis and gasification) that are well suited to relatively small scales of throughput. The electrical power created would either be used onsite to power the paper making process or alternatively exported to the national grid, and the surplus heat created could also be used onsite or exported to a local customer. The focus of this paper is to give a general overview of the project progress so far and will present the experimental results of the most successful thermal conversion trials carried out by this work to date.

***Application:*** The research provides both paper mills and energy providers with methodologies to condition their waste materials for conversion into useful energy. The research also opens up new markets for gasifier and pyrolysis equipment manufacturers and suppliers.

Every day, the world consumes vast quantities of energy from fossil fuels. This is now placing immense pressure on our planet's natural resources, and the $CO_2$ produced from the combustion of fossil fuels is widely believed to be the principal cause of climate change. Furthermore, there are increasing concerns over the price and security of supply of petroleum and natural gas. Therefore, any attempt to decrease the demand for fossil fuel reserves is considered to be beneficial.

The paper industry is a significant user of energy in the form of electricity and heat to power machinery and to dry paper sheets. According to the UK Department of Energy and Climate Change [2], in 2008 the pulp and paper industry within the UK was ranked 19th out of the 93 highest fuel consuming industrial sectors, and consumed a crude oil equivalent of 1.8 million metric tons. Furthermore, the total energy input at UK-based paper mills accounts for approximately 13% of operational costs [3]. As the cost for producing this energy increases year upon year, many UK-based paper mills are finding it increasingly difficult to remain profitable, and this has led to the closure of lower tonnage operations that manufacture commodity grade paper and board products. It is extremely difficult to reduce the high energy demand from this industry without compromising the rate of production and quality of the papermaking process itself. There is therefore increasing interest in alternative lower cost methods of providing the energy.

In recent years, there have been significant efforts by paper manufacturers to make their process more sustainable by increasing the use of recycled paper and board (recovered fiber) as a feedstock. The amount of recovered paper used by UK paper mills as a proportion of their total output stands at approximately 72%, which is a figure believed to be close to the maximum achievable [3]. However, the use of recovered fiber feedstocks results in large volumes of wastes such as rejected plastics, fibers and other coarse materials, "stickies" (adhesive residues), and, in the case of newsprint and tissue mills, deinking sludge (mainly fibers, minerals, and ink). Up until now, these have been disposed of by landspreading or incineration (combustion) [4].

Landfilling of biogenic waste in the UK is fast becoming an unacceptable method of disposal and in some countries, such as Germany and the Netherlands, the disposal of certain types of paper mill wastes in this way has already been banned [5]. Furthermore, landfilling costs are increasing year over year, making this disposal method less feasible economically. Some paper mills have tried to reduce this cost by landspreading a proportion of their sludge [5-7], or by supplying deinking sludge for further processing to become cattle bedding.

A small number of the larger mills (>400000 tpy) incinerate and therefore reduce the volume of their waste. However, due to the low calorific value of some waste fractions, such as deinking sludge (typically 4-7 MJ/kg), autonomous combustion systems cannot be sustained on this fuel alone; therefore,

co-firing with a higher calorific value support fuel is essential. For this purpose, some mills create methane from the anaerobic digestion of waste water and other mills import natural gas, although the latter makes this process both costly and unsustainable. Furthermore, the implementation of a combined heat and power (CHP) combustion system at relatively small scales of paper production (<100000 tpy) is considered to be highly inefficient.

The challenge remains that if UK paper mills wish to further improve the sustainability of their process, they must implement a cost effective waste management strategy that reduces dependency on fossil fuels and mitigates environmental impact.

## PROJECT DESCRIPTION

The aim of the work is to create and optimize a CHP system for recovered fiber paper mills that can convert waste materials (rejects and, where appropriate, deinking sludge) into useful energy products in the most cost effective and efficient way. This work is being carried out under an industrial Cooperative Award in Science and Engineering (CASE) granted by the Engineering and Physical Science Research Council (EPSRC). The work was carried out in collaboration with three UK recovered fiber paper mills – Aylesford Newsprint (Aylesford, England), Smurfit Kappa SSK (Nechells, England), and Kimberly-Clark Flint (Flint, Wales) – together with Biomass Engineering Limited, a UK gasifier manufacturer.

The first stage of the project will analyze characteristics of the waste fractions produced from each mill in terms of their proximate and ultimate compositions and energy content, and develop methods to condition and pretreat the wastes to enable thermal conversion. Then, through trials at pilot scale with both fixed bed downdraft gasification and intermediate pyrolysis systems, the energy recovered from selected wastes and co-fired waste blends in the form of producer gas and pyrolysis oil will be quantified. Once the optimal process route has been established, models to quantify economic gain (return on investment) and environmental impact (carbon footprint) will be developed. The final stage will be an implementation study at each participating mill, including the pre-processing of the wastes, opportunities for utilizing the heat product and/or surplus heat from elsewhere in the mill, thermal conversion, and full integration of the energy products. The focus of this paper is to give a general overview of the project progress so far and to present the experimental results of the most successful thermal conversion trials carried out to date.

## MATERIALS AND METHODS

### *Feedstock characterization*

The wastes that are of priority to recovered fiber mills are reject materials such as waste plastics, metals, and glass (all mills); sludges from primary and secondary biological treatment (mills with on site effluent treatment); and deinking sludge (newsprint and tissue).



*1. De-watered deinking sludge.*

Deinking Sludge

Mixed office waste and news and pams feedstock contain a large fraction of inorganic substances, including printing and writing inks, dyes, and fillers like kaolin ($Al_2O_3$, $SiO_2$, $H_2O$), talc ($Mg_3Si_4O_{10}(OH)_2$), calcium carbonate ($CaCO_3$), and clays that are added to improve printability, smoothness, opacity, and appearance of the finished paper product. The resulting deinking sludge (**Fig. 1**) has a high moisture content that is reduced to approximately 35-40 wt% after de-watering; high ash content between 40-70 wt%, which is predominately calcium based; and a low calorific value (4-7 MJ/Kg).

The high ash content, along with the very low calorific value, of deinking sludge makes the application of this waste for use as a fuel extremely challenging.

Reject Waste

When recovered paper and board is brought into a mill, it often contains large amounts of other waste, such as plastic, metal, and glass. The wet reject material, which can contain moisture content in excess of 70%, is placed in large skips or compactors or is further de-watered using presses before being transported to landfill sites.

The composition of rejects varies between mills and is dependent on the recovered fiber quality and process used at the mill. For example, a brown paper and tissue mill's pulper rejects will often contain mainly plastic and paper fibers, whereas a newsprint mill is more heterogeneous and may see larger amounts of textiles, metal, and glass. Approximately 5% of a typical newsprint mill's waste will be comprised of these materials and this can equate to as much as 5000 dry metric tons per year [2]. The extreme heterogeneous nature of the waste, along with its day-to-day variability, imposes the requirement for costly pre-processing if the material is to be used as a fuel. However, unlike deinking sludge, reject wastes (once dry) generally have a high calorific value, typically 16-25 (MJ/Kg) and a low ash content (<10 wt%). **Figure 2** shows typical reject material produced from a newsprint mill.

The initial stage of work required samples of reject waste



*2. Light rejects generated from a newsprint paper mill.*

(and where appropriate, deinking sludge) to be acquired from each participating mill. Detailed characterization of these waste streams were performed to determine proximate composition (moisture, volatiles, fixed carbon, ash and char contents), ultimate composition (H, N, S, O, and Cl contents), calorific value, and ash metal analysis. In addition, reject material was also generally characterized to determine the relative proportions of glass, metal, plastics, fiber, and other materials present. This stage of work was necessary to assess the thermal behavior of each waste stream.

### Feedstock preparation

Wastes produced by paper mills cannot be used directly as a feedstock for thermal conversion, either by gasification or pyrolysis, without some degree of pretreatment. However, it is important to minimize the necessary pretreatment steps for economic reasons. All previously described wastes have high moisture content at the point of extraction. High moisture containing fuels give rise to high water content product gases, with consequently reduced calorific value. Therefore, moisture must be reduced significantly in order to obtain high thermal efficiencies in all thermal conversion systems.

A maximum moisture content of 15 wt% is recommended for gasification and pyrolysis processes. To reach this level of moisture, further evaporative drying is required. The drying of various paper waste streams can be achieved in many different ways, some of which implement the use of fluidized beds, rotary drum dryers, or paddle dryers. Drying of paper industry wastes like deinking sludge is a well demonstrated technology and is described in detail elsewhere [8-10]. In this work, drying of each waste stream was achieved using rotary drum driers. There currently exists a wide variety of configurations and styles for rotary dryers, but the preferred configuration is the heating of agitated material in a continuous rotating drum that serves the purpose of improved heat transfer efficiency by exposing more surface area of the material to the heating medium [8]. This type of dryer is extremely effective in reducing the moisture content of deinking sludge,



*3. Aylesford Newsprint dry deinking sludge pellets created at Aston University.*

and moisture contents as low as 3 wt% have previously been achieved when using this type of dryer. At full scale, the rotary dryer would be directly heated using exhaust gases from the CHP process (either engine exhaust gases or exhaust gases from a combustor downstream). The hot gases would come into direct contact with the wet material, causing lifting and tumbling effects within the dryer while simultaneously driving off moisture.

For pilot scale trials, once the deinking sludge waste was in a dry flaky form, the material required an extra pelletization step before thermal conversion by pyrolysis. However, at full scale this pelletization step would not be required. **Figure 3** shows the dried deinking sludge pellets produced by this work.

On the other hand, the heterogeneous nature of reject material requires significantly more pretreatment to remove contaminants like glass, metal, and other non-combustible matter. In this work, the pretreatment steps applied for the rejects involved manual sorting to remove non-ferrous metals like aluminium cans and other large objects, including glass bottles, stones, and heavy objects. The rejects were then further sorted on magnetic lines to remove other ferrous metals such as staples, paper clips, etc. The residual material consisting of mainly plastics and fibers were then size reduced, dried, and pelletized before the material was ready for thermal conversion trials. The final product was a reject pellet with a total plastic content of 15-18 wt%; calorific value of 18-22 MJ/kg; an ash content of less than 10 wt%; a size range of 6 mm diameter by 15-20 mm length; a moisture content of less than 10 wt%; a total volatile content of 70-80 wt%; a chlorine content of less than 3 wt%; and an overall bulk density of 494 kg/m$^3$.

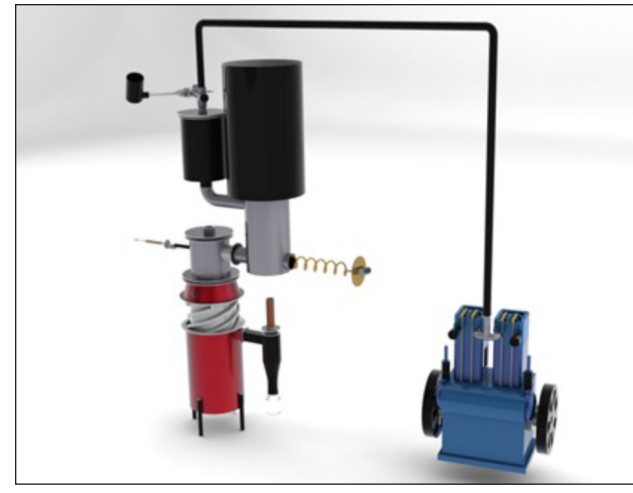
The reject pellets produced by this work were specifically engineered to contain a low plastic content and a high fiber content, which is believed to be the key ingredient for successful gasification of this type of material, as it is thought that it reduces agglomeration problems that are frequently encountered when gasifying fuels with higher plastic concentrations. **Figure 4** shows the Smurfit Kappa SSK reject pellets produced by this work.

### Thermal conversion trials

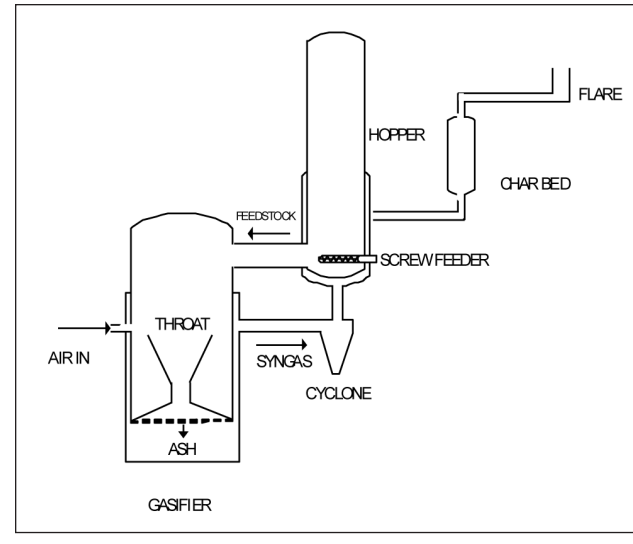
There are two advanced thermal conversion strategies that were explored in this work, namely fixed bed downdraft gasification and intermediate pyrolysis. For pyrolysis, deinking sludge was used as the feedstock, and for gasification reject



*4. Smurfit Kappa SSK fuel reject pellets.*



*5. GEK fixed bed downdraft gasifier coupled to a diesel Lister engine*




*6. Schematic drawing of the GEK gasifier unit*

pellets, deinking sludge and co-fired blends of the two were tested to determine the feasibility of each process and to establish the optimal process route.

### *Fixed bed downdraft gasification*

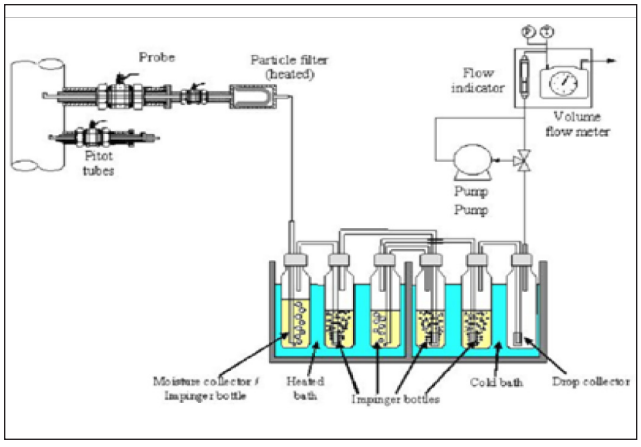
Gasification is not a new technology, although its application in the pulp and paper industry is considered to be in the early stages of development [8]. Gasification offers advantages compared with combustion, such as higher efficiencies and reduced environmental impact. The preferred configuration for small-scale distributed power generation <5 MW thermal is the standard Imbert type fixed bed downdraft gasifier coupled to an internal combustion engine. This was selected as the preferred configuration, as it is well suited to process all the tonnages of wastes from the candidate mills.

Gasification is the conversion of a fuel source into a fuel gas (called a producer gas) that can be used in heat, power, or combined heat and power applications [11]. The process of gasification has also been called "starved combustion." The ultimate creation of NOx (nitrogen oxides), dioxins, and SOx (sulfur oxides) in downstream combustion equipment is much more easily controlled in this process route than in direct combustion [11].

A downdraft gasifier converts prepared pelletized or briquetted fuel into producer gas, which is mainly composed of combustible gases (CO, $H_2$ and $CH_4$). This is then conditioned to remove traces of "tars" and dust particles before being cooled and supplied to a gas engine, either a modified diesel engine or a liquefied petroleum gas (LPG) engine. The complete system consists of fuel handling (conveying, drying, pelletizing, and feeding), gasification (gasifier, char and ash removal, gas conditioning and cooling, gas storage) and power generation (single fuel gas engine or modified diesel engine).

The processing of wastes in this project was carried out using a small scale gasifier, the GEK (Gasifier Experimenter's Kit) designed and supplied by All Power Labs (Berkeley, CA, USA). This is a fixed bed downdraft gasifier that can process a pelletized feed at a maximum rate of 10 kg/h. The unit is comprised of a hopper, dryer, gasifier, filter, and outlet piping, which allows processed producer gas to be routed directly to an engine (in this case, a diesel Lister engine and the gasification medium of air [**Fig. 5**]). **Figure 6** provides a schematic drawing of the GEK gasifier unit.

Downdraft gasification has an advantage over other gasification technologies in that it produces high quantities of permanent gases and lower amounts of tars, which can form deposits in downstream equipment and cause clogging and fouling. Tars can be problematic in a gasification system, so their quantification is essential in this work. Tar was quantified by a tar sampling system in which an isokinetic sample of producer gas is removed from the gasifier and is routed through impinger bottles that condense the tars under low temperatures and by the use of an iso-propanol extraction solvent. Tar removed was subsequently quantified gravimetrically. The remaining clean producer gas was then routed through a mass flowmeter and then directly into a GC-TCD for detection and quantification of $H_2$, CO, $CO_2$, $CH_4$ and $N_2$




*7. Producer gas tar cleaning system [12].*



*8. Pyroformer intermediate pyrolysis reactor at Aston University.*

gas compositions (**Fig. 7**).

In order to achieve successful gasification with both deinking sludge and rejects, it was necessary to co-fire these wastes with a tertiary support fuel, and in this work the fuel of choice was mixed wood chips obtained from a local UK-based wood fuel supplier. At full scale, it is envisaged that paper mills could create deinking sludge and reject briquettes that could be sold as a fuel to existing wood gasifier plants. Alternatively, waste wood could be brought into a paper mill as a replacement for natural gas. Using wood chips in this way is a sustainable solution that would benefit a mill, as increasing the organic component of the feedstock would in turn generate increased revenue from the trading of Renewable Obligation Certificates (ROCs).

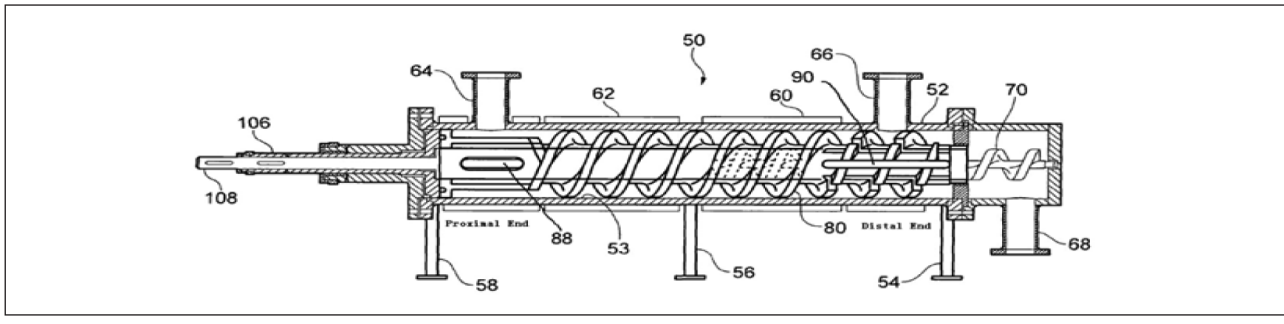
At full scale, a typical gasification application for paper industry waste feedstocks would be a CHP plant with a total feed input of 500 kg/h and an electrical output of approximately 500 kWe (comprised of two 250 kWe gasifier units).

### *Intermediate Pyrolysis*

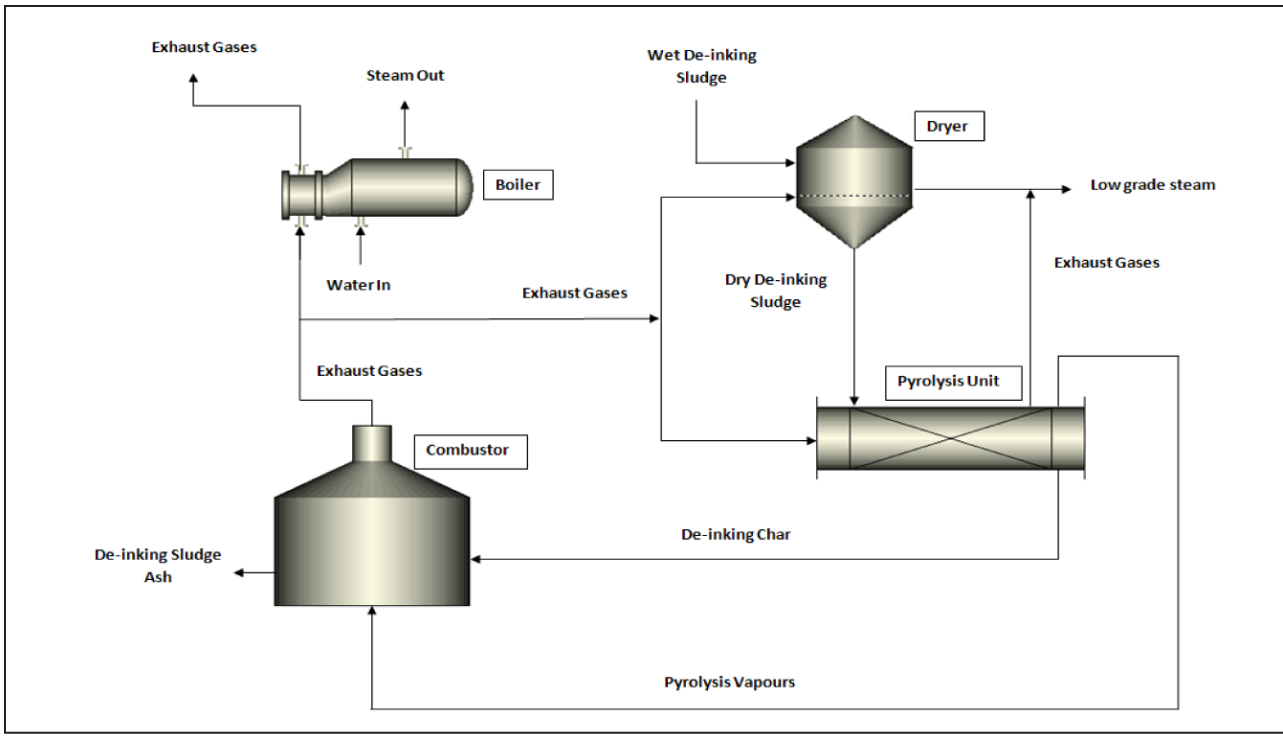
Pyrolysis is defined as the thermal decomposition of organic matter in the complete absence of oxygen, and intermediate pyrolysis occurs under moderate residence times (10-15 min) and reaction temperatures (400°C -550°C). Intermediate pyrolysis produces large quantities of condensable organic oils known as bio-oil. These oils are easier to transport and store than producer gas from gasification. Once produced, bio-oil can either be introduced into a modified diesel engine or further upgraded to run in conventional engines. Intermediate pyrolysis also has the potential to generate moderate amounts of permanent combustible gases, and these can also be premixed with air before entering a modified engine. A by-product from intermediate pyrolysis is a relatively large quantity of char, and this can be used as a fuel or possibly returned to the soil ("bio-char") for carbon sequestration or as a fertilizer.

For the purpose of this work, a recently designed and patented "Pyroformer" reactor was used [13]. The unit as installed at Aston is shown in **Fig. 8**.

The Pyroformer design is essentially an auger pyrolysis reactor with two counter rotating screws that can process a feed in an inert atmosphere of nitrogen at a rate of up to 20 kg/h (at lab scale). The reactor is heated externally by electrical heating bands, and the feed moves through the screw conveyor system while being heated to the specified pyrolysis temperature. The char formed is largely inert and drops out at the opposite end of the reactor. Pyrolysis gases that form pass through the gas outlet into filter candles that remove solids and small particulates. Vapors are then routed into a shell and tube water cooled condenser where they are condensed.




*9. The Pyroformer intermediate pyrolysis reactor, Aston University. (106, 108 - internal screw shaft; 64 - feed inlet pipe; 62, 60, 52, 50 - electrical heating bands; 58, 56, 54 - Pyroformer supports; 88, 90 - external screw slots; 80 - external screw; 70 - internal screw; 68 - solid drop out pipe; 66 - gas outlet pipe.)*




*10. Proposed deinking pyrolysis process.*

Permanent gases continue to move through the system into an electrostatic precipitator where aerosols are condensed out. The clean combustible gas is then routed to a GC-TCD for detection. **Figure 9** provides a schematic drawing of the internal mechanics of the pyrolysis unit.

This process is well suited to deinking sludge, as it can tolerate fuels with low calorific values and high ash contents because it has the ability to separate the solid and gas fractions that are formed. Therefore, the pyrolysis of deinking sludge was selected as the ideal candidate for trials using the Pyroformer.

At full scale, it is envisaged that the inert solids formed from the pyrolysis of deinking sludge would be co-fired with the hot pyrolysis vapors that are formed from the process in a combustion unit downstream. The ash product formed could then be sold to cement industries as a cement or concrete admixture. Some of the hot exhaust gases from the combustion unit would be required to run the drying and pyrolysis process itself, with the majority of exhaust gases being routed to either a gas turbine or boiler for electricity generation. Processing deinking sludge in this way would significantly reduce the natural gas requirement of mills that currently combust their sludge using natural gas. **Figure 10** shows one configuration for the process.

At full scale, the advantage of this type of intermediate pyrolysis over fixed bed gasification is that the feedstock does not need to be pelletized, although drying is still necessary. It is also more tolerant of feedstock variability. A full-scale system based on this technology could process up to 20000 dry metric tons/year, and multiple units in parallel are possible for higher tonnages.

## EXPERIMENTAL RESULTS AND DISCUSSION

### *Feedstock characterization*

**Table I** presents the proximate and ultimate analysis of the pretreated deinking sludge and reject fuel pellet feedstocks used in trials to date.

It is observed that the deinking sludge from both the newsprint mill and tissue mill were similar. Also, notable is the similarity between the reject pellets from the newsprint mill and the brown paper mill. Deinking sludge has a very low calorific value and a very high ash content, which makes this feedstock more suitable for use in the pyrolysis unit as opposed to the gasifier. The reject fuel pellets have a higher calorific value when compared with mixed wood chips, and this is due to the presence of plastics within the pellets. The rejects also have a much lower ash content compared to deinking sludge, but the ash is significantly higher than for wood chips. The high calorific value of the rejects makes this a more suitable fuel for use in the gasifier, as the increased calorific value produces a product gas with a higher heating value than that from wood gasification. At full scale, the increased amount of ash present in the reject pellets would require the need for a continuous ash removal system within the gasifier unit.

From Table I, the total volatile fraction and fixed carbon content of the reject pellets can also be described as comparable with wood chips. Chlorine content of the rejects is observed to be higher when compared to wood chips, and this is thought to be as a result of residual PVC material in the plastic pellets.

| | Mixed Wood Chips | Aylesford Newsprint Deinking Sludge | Kimberly-Clark Flint Deinking Sludge | Aylesford Newsprint Reject Pellets | Smurfit Kappa SSK Reject Pellets |
|---|---|---|---|---|---|
| **Proximate Analysis, wt% (dry basis)** | | | | | |
| Moisture | 3.7 | 1 | 1.3 | <0.2 | 7.6 |
| Volatiles | 86.6 | 46.3 | 55.1 | 83.4 | 73.5 |
| Fixed carbon | 9.4 | 1.1 | <0.1 | 7.2 | 10.1 |
| Ash | 0.3 | 51.6 | 43.6 | 9.4 | 8.8 |
| Gross CV (MJ/Kg) | 15.4 | 6.4 | 7.0 | 18.3 | 22.9 |
| **Ultimate Analysis, wt% (dry basis)** | | | | | |
| Carbon | 45.6 | 21.1 | 21.7 | 60.9 | 53.3 |
| Hydrogen | 5.8 | 2.3 | 2.8 | 3.4 | 7.5 |
| Oxygen* | 48.0 | 24.7 | 29.8 | 23.5 | 29.6 |
| Nitrogen | 0.3 | 0.3 | 2.1 | 0.4 | 0.5 |
| Sulphur | <0.1 | <0.1 | <0.1 | 0.4 | <0.1 |
| Chlorine | <0.1 | <0.1 | <0.1 | 2 | 0.3 |
| * Result obtained by difference | | | | | |

***I. Proximate and ultimate characterization of paper mill waste feedstocks.***

### *Gasification trials*

Numerous gasification trials were carried out using both deinking sludge and rejects acquired from all three collaborating paper mills. Initial trials attempted to gasify the reject pellets solely as a fuel in the GEK. However, these were found to be largely unsuccessful because of agglomeration due to melting of the plastics within the pellets. Agglomeration was found to be mainly within the pyrolysis zone of the gasifier; as the plastics reach this zone they become soft and extremely sticky, causing bridging and binding above the gasifier throat. This subsequently causes increased pressure drop within the gasifier unit and leads ultimately to unsuccessful gasification. One of the most important factors when using the downdraft gasifier is the ability for feedstock to freely move through the unit by gravity. Therefore, initial work focused on determining to what extent the pellets could be co-fired with mixed wood chips before agglomeration occurred.

The most successful of these trials to date is the blending of Smurfit Kappa SSK pulper reject pellets with wood chips. When this test was carried out, a blend of 80 wt% pellets with 20 wt% wood chips was found to gasify successfully for several hours with no performance problems, and a consistent flare was achieved throughout the duration of the trial. It is the composition of this particular feedstock that is thought to be the key parameter for its successful gasification. **Table II** shows the composition of producer gas formed. The heating value of 7.3 MJ/Nm$^3$ is higher than that usually obtained from wood gasification (typically 4-6 MJ/Nm$^3$).

| Normalized Producer Gas Composition | Vol % |
|---|---|
| $H_2$ | 16.24 |
| N2 | 42.49 |
| CO | 23.34 |
| $CO_2$ | 12.71 |
| $CH_4$ | 5.21 |
| Gross heating value (MJ/Nm$^3$) | 7.3 |

***II. Normalized producer gas compositions from the gasification of 80 wt% Smurfit Kappa SSK reject pellets with 20 wt% mixed wood chips.***

Tar and water condensate formation during the run was also measured immediately at the gasifier exit, and this was found to be 6 g/Nm$^3$ and 21 g/Nm$^3$, respectively. For tar, this value is substantially higher than that observed from wood gasification, which typically produces around 2 g/Nm$^3$ in this type of gasifier. However, at full scale, careful control of gasification temperatures, along with the use of downstream tar clean up equipment like scrubbers, filters, or tar crackers has been shown to reduce the amount of tar entrained in the producer gas to acceptable levels for use in an engine. In this

work, tar clean up was achieved using a carbon absorption filter, but tar levels downstream of the filter were not measured.

On the basis of these results, the potential to carry out full scale downdraft gasification of brown paper mill pulper rejects at a total throughput of 250 kg/h is currently being explored (sufficient to power a 250 kWe gas engine with residual heat available for drying). The outcome of these trials will be presented in a later paper.

### *Intermediate pyrolysis trials*

This work has developed a method to utilize deinking sludge waste fractions for the onsite production of CHP using the advanced thermal conversion method of intermediate pyrolysis. The main advantage of this process is that it potentially removes the need for paper mills to import large quantities of natural gas to co-fire sludge in a combustion unit.

Due to the high ash content and extremely low calorific value of deinking sludge, along with the Pyroformer's suitability for continuous ash removal, intermediate pyrolysis was selected as the preferred system for the processing of this waste. Trials were carried out in the Pyroformer using both Aylesford Newsprint and Kimberly-Clark Flint deinking sludge, and the results produced from both mills were very similar. Pyrolysis trials were carried out at a temperature of 450oC under an inert atmosphere of nitrogen. The volatiles produced were routed into hot gas filter candles maintained at the same temperature in order to remove fly ash entrained in the gas. Next, the gas was passed though a shell and tube water cooled condenser to condense out the water and condensable organic vapors. The remainder of the permanent gases were routed into an electrostatic precipitator for light organic aerosol removal, and then to GC-TCD for CO, $CO_2$, $N_2$, and $H_2$ detection.

After condensing of the organic vapors formed, the pyrolysis bio-oil was found to be of a high quality with a very high calorific value (close to 40 MJ/kg, which is comparable to diesel) after removal of an easily separated aqueous phase. The oil was separated from the aqueous phase by gravity settling and was then characterized for its energy content, ultimate compositions, and fuel properties, which are presented in **Tables III** and **IV**, respectively.

From Table III, it is observed that the oxygen content of deinking sludge pyrolysis oil (10%-11%) is much lower than pyrolysis oil obtained from traditional biomass feedstocks like wood or straw (typically 30%-50%). Lower oxygen content increases the calorific value and stability of the oil.

In addition, a sample of the oil was dissolved in an ethanol solvent and further tested using liquid GCMS. The major components were found to be benzene, toluene, styrene, and phenolic compounds, as well as some fatty acid methyl esters.

| | Aylesford Newsprint Deinking Sludge Bio-oil Result, wt% | Kimberly-Clark Flint Deinking Sludge Bio-oil Result, wt% |
|---|---|---|
| Carbon | 78.71 | 76.58 |
| Hydrogen | 10.08 | 8.38 |
| Nitrogen | 1.02 | 1.86 |
| Sulphur | 0.55 | 0.58 |
| Oxygen | 10.08 | 11.27 |
| Ash | <0.02 | <0.02 |
| Gross heating value, MJ/Kg | 37 | 36 |

***III. Ultimate analysis and gross heating value of Aylesford Newsprint and Kimberly-Clark Flint deinking sludge bio-oil.***

| | Units | Aylesford Newsprint Deinking Sludge Bio-oil Result, wt% | Kimberly-Clark Flint Deinking Sludge Bio-oil Result, wt% |
|---|---|---|---|
| Water content | % | 4 | 3 |
| pH | - | 4.8 | 4.7 |
| Flash point | °C | 168 | 160 |
| Density | kg/m$^3$ | 980 | 984 |
| Cetane index | - | n/a | 23 |
| Kinematic viscosity @ 40°C | cSt | 12.3 | 9 |
| Total acid number | mgKOH/g | 26.0 | 32.8 |
| Copper corrosion | - | 3A | 2C |
| Carbon residue | wt % | 3.9 | 4.6 |

***IV. Aylesford Newsprint and Kimberly-Clark Flint deinking sludge bio-oil fuel properties.***

| Normalized Pyrolysis Gas Composition | Aylesford Newsprint Deinking Sludge, Vol % | Kimberly-Clark Flint Deinking Sludge, Vol % |
|---|---|---|
| $H_2$ | – | 1.9 |
| CO | 22.7 | 25.5 |
| $CO_2$ | 71.2 | 66.3 |
| $CH_4$ | 6.1 | 6.3 |
| Gross heating value, $MJ/Nm^3$ | 5.5 | 6.2 |

***V. Normalized pyrolysis gas composition from the pyrolysis of Aylesford Newsprint deinking sludge.***

| | Aylesford Newsprint Deinking Sludge Solid Residue Result, wt% | Kimberly-Clark Flint Deinking Sludge Solid Residue Result, wt% |
|---|---|---|
| Carbon | 17.12 | 20.02 |
| Hydrogen | 1.13 | 2.19 |
| Nitrogen | 0.26 | 0.38 |
| Sulphur | <0.1 | <0.1 |
| Oxygen* | 21.49 | 23.91 |
| Ash | 60 | 53.5 |
| Gross heating value, MJ/Kg | 3.3 | 4.9 |
| * Result obtained by difference | | |

***VI. Pyrolysis deinking sludge solid residue ultimate characterization and energy content.***

Analysis of the oil to determine its fuel properties were also carried out. Table IV shows the fuel properties of the pyrolysis oils produced. Table IV also demonstrates that bio-oil obtained from deinking sludge contains a lower water content than pyrolysis oil from traditional biomass feedstocks, making it a fuel with improved combustion characteristics. Furthermore, the viscosity of the oil, as well as the total acid number, is significantly less than what is usually formed from biomass pyrolysis oils, which gives this oil improved flow characteristics along with making the fuel less corrosive to equipment component parts.

A gas analysis using a GC-TCD analyzer was carried out on the permanent gases formed and the normalized gas compositions along with the calorific value was subsequently determined. **Table V** presents the average gas analysis results.

The residual solids from the pyrolysis trials were mostly inert, with a majority being calcium carbonate. The solid residue from the process was characterized for its ultimate composition and energy content, and **Table VI** presents the results.

A typical mass balance of this process at steady state produces approximately 9 wt% condensable organic vapors (pyrolysis oil), 1 wt% aqueous phase, and 15 wt% permanent gases, with the remaining 75 wt% being the solid inert residues, mainly calcium based. An implementation study is now being carried out to analyze how this process would integrate into a typical mill and the associated economic impact, but initial indications are that considerable savings could be made, particularly from the reduced or eliminated use of natural gas for co-firing. The opportunity exists to sell an alkaline ash to the construction industry or for use as animal bedding.The possibility of using the ash product as a catalyst is also being explored. The results of the study will be presented in a later paper.

## FUTURE CHALLENGES

Distributed power generation that converts paper industry residues into energy using advanced thermal conversion methods is attractive to paper companies seeking to reduce costs and demonstrate the sustainability of their manufacturing process. It is hoped that the present project will be able to advance this case by meeting the following challenges:

- To successfully demonstrate both the gasification and pyrolysis of selected feedstocks and feedstock blends at a range of scales.
- To undertake an implementation study of attractive options at candidate mills including full economic analysis.
- To examine the potential for the paper industry to contribute to EU 2010 targets for 10% of electricity from renewable sources (or 2020 targets of 20% of electricity from renewable sources). **TJ**

## ACKNOWLEDGEMENTS

The authors would like to thank the Engineering and Physical Science Research Council (EPSRC), Aylesford Newsprint, Smurfit Kappa SSK and Kimberly-Clark Flint for sponsoring the project. Their contributions are greatly acknowledged.

## LITERATURE CITED

1. Confederation of European Paper Industry, "Sustainability Report 2009," CEPI, Brussels, Belgium, 2009, p. 16. Available [Online] www.cepi.org/Objects/1/Files/CEPI-Report09.pdf> [21October2011].
2. Department of Energy and Climate Change, "Fuel Use by 93 Economic Sectors," 2008, London, UK. Available [Online] www.decc.gov.uk/default.aspx> [29June2010].
3. Kay, M., *Pulp Pap. Int.* 49(2): 21(2007)
4. Mozaffari, E., Kinuthia, J.M., Bai, J., et al., *Cem. Concr. Res.* 39(10): 942(2009).
5. Monte, M.C., Fuente, E., Blanco, A., et al., *Waste Manage.* 29(1): 293(2009).
6. Mendez, A., Fidalgo, J.M., Guerrero, F., et al., *J. Anal. Appl. Pyrolysis* 86(1): 66(2009)
7. Caputo, A.C. and Pelagagge, P.M., *J. Hazard. Mater.* 8(3): 265(2001).

8. CanmetENERGY Technology Centre, "Pulp and paper sludge to energy: Preliminary assessment of technologies," ADI Limited Report: (34) 0173-479.1, 2005 p. 48.

9. Deng,W.-Y., Yan, J.-H., Li, X.-D., et al., *J. Hazard. Mater.* 162(1): 186(2009)

10. Alina Stoica, A., Sandberg, M., and Holby, O., *Bioresour. Technol.* 100(14): 3497(2009)

11. US Department of Energy, *Handbook of Biomass Downdraft Gasifier Engine Systems*, US Government, Washington DC, USA, 1988.

12. CEN Tar Protocol, 2005. Available [Online] www.tarweb.net/results/pdf/Technical-Report-version-3_8-final.pdf >[17July2010].

13. Hornung, A., et al., Great Britain Patent Application Number: GB 0808739.7 (May 15, 2009). World Patent Application WO 2009/138757 (November 19, 2009).

## ABOUT THE AUTHORS



***Ouadi***



***Brammer***



***Hornung***



***Kay***

The paper industry is a significant producer of waste, which is currently disposed of by landspread, landfill, or incineration. Paper mills are also significant users of energy in the form of electricity and heat. As energy and disposal costs increase year upon year, many paper mills are struggling to remain profitable, and this has led to the closure of many mills. Therefore, we chose to research the utilization of these waste streams for their thermochemical conversion into useful energy products, as it is of great importance for future sustainable development.

Previously, there has been limited research into the utilization of wastes derived from paper mills for combined heat and power (CHP) applications. However, our research complements some background information into the potential of gasification to process paper industry wastes (Kay, M., *Pulp Pap. Int.* 49[2]: 21[2007]). Overall, the main difference of this work is that it has identified the optimal process route for each particular waste stream generated at paper mills by applying both gasification and pyrolysis technologies at a capacity >5kg/h and has presented the experimental findings.

The most difficult aspect of the research was solving the technical difficulties associated with lab-related issues and doing so within the allocated budget. This was addressed by designing, building and commissioning much of the equipment and instrumentation that was required to carry out the research

This research in principle has discovered two feasible processes for producing useful energy from paper industry rejects and deinking sludge wastes. An unexpected, yet most interesting, finding was the large energy content and quality of the oil produced from the pyrolysis of deinking sludge.

Paper mills that generate significant quantities of rejects and de-inking sludge wastes can benefit from this research as it offers an alternative disposal solution for their waste streams that can potentially generate large quantities of useful energy. At the same time, there is significant potential to reduce the carbon footprint of the paper product.

The next step in this research is to optimize the proposed processes. Research will be carried out in large scale systems at a range of different parameters to identify how the developed processes can be modified and tailored to meet each mill's specific energy demands. An economical evaluation of each proposed process will also be developed.

*Ouadi is a research student, Brammer is a lecturer, and Hornung is a professor at the European Bioenergy Research Institute (EBRI), Aston University, Birmingham, UK. Kay is chief consultant with PIRA International, Leatherhead, Surrey, UK. Email Kay at martin.kay@pira-international.com.*