

1 **DETERMINATION OF RENEWABLE ENERGY YIELD FROM MIXED WASTE**
2 **MATERIAL FROM THE USE OF NOVEL IMAGE ANALYSIS METHODS**

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Abstract

Two novel techniques are presented in this study which together promise to provide a system able to determine the renewable energy potential of mixed waste materials. An image analysis tool was applied to two waste samples prepared using known quantities of source-segregated recyclable materials. The technique was used to determine the composition of the wastes, where through the use of waste component properties the biogenic content of the samples was calculated. The percentage renewable energy determined by image analysis for each sample was accurate to within 5% of the actual values calculated. Microwave-based multiple-point imaging (AutoHarvest) was used to demonstrate the ability of such a technique to determine the moisture content of mixed samples. This proof-of-concept experiment was shown to produce moisture measurement accurate to within 10%. Overall, the image analysis tool was able to determine the renewable energy potential of the mixed samples, and the AutoHarvest should enable the net calorific value calculations through the provision of moisture content measurements. The proposed system is suitable for combustion facilities, and enables the operator to understand the renewable energy potential of the waste prior to combustion.

Keywords- Biogenic content, renewable energy, mixed wastes, image analysis, energy from waste

1. Introduction

The development of renewable energy technologies has become more prominent in recent years. This is due in part to European Union (EU) and global movement away from traditional energy generation from fossil fuels and the associated greenhouse gas (GHG) emissions (Del Río, 2011; Garg et al., 2009; Shafiullah et al., 2012; Tükenmez and Demireli, 2012), and also to the challenging target set by the European Union of producing 20% of electricity from renewable sources by 2020 (Council of the European Union, 2009; Lupa, 2011). Energy produced from biomass (Becidan et al., 2007; Defra, 2008; Mabee et al., 2011; Panoutsou et al., 2009; Qiao et al., 2011; Whittaker et al., 2011) and the bio-based fraction of wastes (Séverin et al., 2010; Velis et al., 2012; Wagland et al., 2011) presents a sustainable and secure solution to the renewable energy strategies.

Recovering value from waste materials is of key importance for the development of a sustainable future. Whilst the reuse, recovery and recycling of wastes is of interest, a significant proportion of residual waste remains that is either non-recoverable for various reasons, or has no commodity value. Therefore the thermal treatment of residual wastes is a management option that is popular across Europe, and is becoming more prominent in the UK as policy incentivises moving away from landfill disposal and towards the generation of renewable energy.

In Europe, national and international targets have been set up for waste recycling, recovery and diversion from landfill (Burnley et al., 2007), which in combination contribute to an integrated waste management system (Grosso et al., 2010). Likewise, existing targets regarding renewable energy production can include energy from biomass

1 and the biomass (or ‘bio-based’) fraction of waste (Wagland et al., 2011). When
2 considering the mixed waste materials, it is critical to understand not only the biogenic
3 carbon content of the waste, but also the energy potential or yield from the bio-based
4 fraction. This is due to the renewable energy targets set (Council of the European Union,
5 2009), and the need to demonstrate the quantity of renewable energy generated from
6 mixed fuels in order to obtain any available financial incentives (such as the renewable
7 obligation certificates in the UK (Ofgem, 2009). Biogenic carbon is defined as the
8 fraction of total carbon present in a material that has been produced naturally by living
9 organisms, but not fossilised or fossil-derived (European Committee for Standardisation,
10 2007). A number of methods exist to determine the biogenic fraction of waste-derived
11 fuels, such as the manual-sorting and selective dissolution test methods (British standards
12 Institute, 2011c; Séverin et al., 2010), although the determination of ^{14}C by accelerated
13 mass spectrometry [AMS] is generally considered to be the most accurate (European
14 Committee for Standardisation, 2007; Fellner et al., 2007). However, these methods do
15 not link the biogenic fraction to the energy content of the sample.

16 One such approach in determining the biogenic content of a mixed waste material
17 would be by determining the physical composition of the mixed wastes, and then
18 matching each component to the biogenic carbon content, as determined by the ^{14}C
19 content. A novel test method has been recently developed by Wagland *et al.* (2012)
20 which can determine the composition of mixed wastes by a simple image analysis
21 technique (Wagland et al., 2012). This approach utilises Erdas Imagine™ v9.3 software
22 to process 12 mega pixel digital pictures by image correction and the placement of a dot-
23 grid over the image. The work described by Wagland *et al.* (2012) assesses a 1 m² area of

1 mixed waste; the density of each component is used together with the area covered by
2 each component in order to calculate the percentage composition of the total waste
3 material by weight. A very strong relationship was demonstrated between the hand
4 sorted data and the results yielded by the image analysis method, with a mean correlation
5 (r) of 0.91 ($p < 0.05$) (Wagland et al., 2012).

6 The net calorific value (or 'lower heating value') of a fuel cannot be determined
7 analytically, but is calculated from the gross calorific value ('higher heating value') and
8 the content of moisture, carbon, hydrogen, oxygen and nitrogen (British Standards
9 Institute, 2011a). However, the accurate determination of the net calorific value of the
10 mixed waste requires an accurate measurement of moisture content across and through
11 the waste volume. Optical technologies are not suitable for penetrating below the surface
12 of the waste, and contact methods are difficult to implement in a waste processing
13 environment. The most suitable non-contact technology for moisture measurement of the
14 waste stream is the microwave moisture sensor: two such examples are the RadarTron
15 2550D (manufactured by ScaleTron) and Hydroprobe (manufactured by Hyronix).
16 However, all currently available moisture sensors offer only single point measurement
17 and provide a limited view of the moisture. This study presents a two-dimensional
18 moisture imaging system, termed NPL AutoHarvest, under investigation for its
19 application to waste moisture quantification with a spatial resolution close to one
20 centimetre.

21 The image analysis tool is used to determine the composition and energy from the
22 biogenic fraction of mixed wastes; the AutoHarvest technology is used to estimate the
23 moisture content of waste samples. This study aims to demonstrate that the two

techniques can be combined to accurately determine the potential energy yield from the biogenic fraction of mixed wastes. The biogenic carbon content and the calorific values (gross and net) were determined for each individual component. The moisture content, determined throughout for each component, was used to adjust the net calorific value [NCV]. The NCV accounts for the latent heat of the water vapour formed by evaporation of the moisture within the waste and formed by the combustion of the hydrogen in the fuel. This latent heat is not recoverable in a conventional boiler plant. As such, the NCV represents the energy yield, representing the energy that would be produced in a 100% efficient non-condensing conversion process.

2. Methods

2.1. Waste materials and preparation

The waste components used in this study were gathered from materials collected from the Cranfield campus of Cranfield University. These included source-segregated components [paper, card, aluminium cans and dense plastic], film plastic, green waste, textiles, inert (rubble) and waste wood. The paper used was office paper, the card used was corrugated packaging cardboard, the dense plastics were PET bottles with a small fraction of HDPE lids, and the film plastics used were black bin bags. The textiles were a mixture of different clothing items and the waste wood was taken from pallets.

Each component was then 1) retained for image analysis; 2) dried and dispatched to the National Physical Laboratory [NPL] for microwave analysis for varying moisture content; and 3) dispatched to third party laboratories for analysis.

For the image analysis, the waste components were weighed before being combined to produce two different batches, A and B, of mixed waste (42.7 and 45.5 kg respectively). These batches were chosen to ensure that each waste sample was sufficiently different: thus sample A did not include film plastic and inert; whilst sample B did not include textiles. As a result of this selection and mixing, the composition of each of these batches was known prior to image analysis.

Representative samples of the waste components (ca. 500 g) to be sent to NPL were dried overnight in an oven at 50°C before being individually placed in air-tight containers and delivered to NPL.

The waste components sent to the third party laboratories were not dried before dispatch; they were however prepared by each respective laboratory in accordance with the European standard method statement. Approximately 250 g of each component was sent to Marchwood Scientific for proximate and ultimate analysis; whereas <50 g of each component was used by Beta Analytic for biogenic carbon (^{14}C) analysis. Along with efforts to ensure that the samples delivered to the third party laboratories were representative of the whole batch, the components were analysed individually and were typically the same type (i.e. PET bottles, office paper etc) and so variation was expected to be minimal.

2.2. Proximate, calorific value and biogenic analysis

The moisture and ash content of the samples, along with the gross calorific values [GCV], were analysed in accordance with the relevant standard methods (British Standards Institute, 2011a, b; European Committee for Standardisation, 2010a) at

Marchwood Scientific [Southampton, England]. The net CV [NCV] was calculated from the GCV as defined by the standard method (British Standards Institute, 2011a). GCV analyses are within 5% repeatability, as is required by the standard methodology.

The biogenic carbon fraction was measured, calculated and reported for each sample by Beta Analytic [London, England] in accordance with the accepted standard methods (American Society for Testing Materials, 2012; European Committee for Standardisation, 2007; International Organisation for Standardisation, 2013). The technique used by Beta Analytic requires an accelerated mass spectrometer [AMS]. Here the sample is combusted to form CO₂, which is then converted to graphite by passing over a hot Fe catalyst with H₂. The graphite target is then bombarded by Caesium [Cs] ions to release C ions. The rapid detection of ¹²C⁴⁺, ¹³C⁴⁺ and ¹⁴C⁴⁺ ions allows for the calculation of the ratio of ¹⁴C to ¹²C/¹³C (European Committee for Standardisation, 2007).

2.3. Image analysis

Each of the two waste samples produced were spread evenly to represent a typical conveyor belt as used to transport waste in treatment processing facilities. A 1 m² quadrant was placed over each part of the waste, and a digital image was captured of each section. The quadrant was placed so as to ensure that all waste was covered during this process, whilst avoiding overlap between sections.

The digital images were then processed using Erdas Imagine (v9.3) to crop and geometrically correct the images before placing an 11x11 dot-grid over the image, as described in a previous study (Wagland et al., 2012). Each dot covering each of the

waste component categories was manually selected, and the total number of dots covering each component was counted digitally.

In the previous study (Wagland et al., 2012), individual components of fixed volume (30 litres) were weighed to determine the density (g/cm³) of each component (European Committee for Standardisation, 2010b). However, errors were encountered using this approach, and so in this study the individual components were spread out and subjected to image analysis in order to calculate the mass per dot (kg/dot) for each component. This accounts for the varying thickness of the waste layers, and reduces the errors encountered during the conversion from number of dots to the % composition by weight. The use of a calculated kg/dot over a number of samples (images) means that variations in the thickness of the waste components are essentially averaged out.

2.4. In-line moisture analysis

The dielectric properties of water at microwave frequencies are well documented (Ellison, 2007; Kaatze, 1989). Likewise, the use of microwaves for the measurement of moisture content of materials has been known for some time (Kapilevich et al., 2007; Meyer and Schilz, 1980; Sokoll and Jacob, 2007).

The absorption of a microwave beam by a material sample in air follows the Beer-Lambert law (Hecht, 2001):

$$I_T = I_0 T e^{-ad} \quad (1)$$

Where I_T and I_0 are the transmitted and incident intensities respectively; α is the absorption coefficient, and d is the sample thickness. The coefficient T represents propagation loss at the interface, which may be due to a combination of reflection and scattering, and is dependent on both the angle of incidence and surface roughness. For a plane-parallel homogenous sample with faces that are smooth on the scale of the wavelength and which is positioned normal to the beam, scattering is absent, and T is given by the Fresnel formula (Hecht, 2001):

$$T = 1 - (n-1/n+1)^2 \quad (2)$$

Where n is the refractive index of the sample material. When the above conditions are not met, the value of T will be reduced (except in the special case of Brewster-angle reflection (Hecht, 2001)). For a multi-component material, e.g. composite or containing water, the coefficient α must be replaced by $\alpha_1 C_1 + \alpha_2 C_2 + \alpha_3 C_3 + \dots$, where the subscripts refer to the individual components and C is the fractional concentration of each species.

Transmitted power loss in dB is calculated as:

$$Loss = -10 \log_{10} (I_T/I_0) = -4.34 \log_{10} T(ad) \quad (3)$$

and is additive when the beam passes through several material layers, i.e., for N layers:

$$Loss (N) = 4.34 \log_{10} (T_1 + T_2 + \dots T_N) (\alpha_1 d_1 + \alpha_2 d_2 + \dots A_N d_N) \quad (4)$$

The microwave transmission loss of a mixed stack of materials, such as waste stream, will therefore be determined by the absorptivity, thickness, orientation relative to the beam, and texture of all individual layers in the stack.

The absorption coefficient α has a strong frequency dependence arising from molecular resonances and phonon bands (Huang and Richert, 2008). This is particularly true of liquid water, where absorption rises very steeply with frequency, as seen in Figure 1, which also shows the refractive index of water at relevant frequencies. At the measurement frequency of 5 GHz α_{water} is 2.2 cm^{-1} . Since absorption increases with frequency, selecting a higher frequency increases measurement sensitivity for low water concentrations or for thin sample thickness. Microwave absorption coefficients of dry wood, paper, plastic and fabric are much smaller than that of water (Simonis, 1982), simplifying moisture content calculations. However, since the refractive index of water is also much higher than that of most other waste materials, microwave transmission through multiple layers of waste will also experience loss due to enhanced interface reflection and refraction.

>>>>>>>>>Insert Figure 1<<<<<<<<<<

Figure 1. The absorption coefficient and refractive index of liquid water at microwave frequencies (Segelstein, 1981)

The moisture measurement system comprises a 5 GHz microwave transmitter and receiver placed either side of the sample space and monitoring transmitted power. The NPL AutoHarvest system utilises a linear array of 24 parallel receiving sensors,

1 producing a line image of loss distribution. A 2D loss map is generated by passing the
2 material through the sample space on a conveyor.

3 In order to evaluate the moisture content, the measured loss map must be
4 combined with the optical image analysis as described above. The loss of dry material
5 can then be estimated from the knowledge of material type and thickness; the difference
6 between measured loss and loss calculated for dry material would be attributable to the
7 presence of moisture. For a single layer of material, the effective thickness of the water in
8 the beam path can be calculated from:

$$Loss_{wet} - Loss_{dry} \cong -4.34 \log_{10} T_{dry} (\alpha_{water} d_{water}) \quad (5)$$

11
12 where the approximate sign is due to the fact that T will be different in wet and dry
13 materials, although the difference is not expected to be large: $T_{dry} \approx T_{wet}$.

14 In order to investigate the practical aspects of moisture measurements and to
15 produce some test calibration curves, a simple phantom was designed and its microwave
16 transmission measured using a single transmitter-receiver channel. The phantom was a 5
17 mm thick cellulose sponge, chosen for its high water retention capability and because
18 cellulose has similar microwave properties to a number of waste materials, such as paper,
19 cardboard, wood and natural-fibre textiles. Moisture content of the sponge was
20 determined by its weight. Figure 2 plots the measured microwave loss as a function of
21 sponge weight, and therefore moisture content, for three test frequencies: 5, 16 and 26
22 GHz. The weight of dry sponge was 0.7 g and its microwave loss was 0.2 dB at all test
23 frequencies. As expected from Equation 5, the relationship between loss and moisture

content is linear within measurement error. The scatter in the data is due largely to the difficulty of ensuring a uniform distribution of water across the area of the sponge. It is seen that at higher frequencies the slope is larger, due to increased water absorptivity. Larger slope translates into higher measurements sensitivity. However, increased loss requires larger signal-to-noise ratio in the measurement system: note that in Figure 2 the noise in the data increases greatly when the loss exceeds 40 dB. Therefore the test frequency must be selected with a view to a necessary trade-off between desired measurement sensitivity and available signal-to-noise performance.

>>>>>>>>>Figure 2<<<<<<<<<<<<

Figure 2. Transmission loss as a function of weight of water in a test object (cellulose sponge), measured at 5 GHz, 16 GHz, 26 GHz. Different symbols represent separate experimental runs.

The data indicates the scale of possible errors in measuring moisture content. It may be expected that an uncertainty of ± 2 dB is likely to be present in an industrial in-line system, which would result in a corresponding uncertainty in water content of 17% at 5 GHz, 5% at 16 GHz, and 3% at 26 GHz.

Figure 2 demonstrates the type of calibration curves required to obtain reliable moisture measurement from measured microwave loss. The imaging system must be similarly calibrated for every type of material present in the waste stream, containing the expected range of moisture levels. The material data will be combined with independent measurements of thickness, or mass, of different types of materials. A statistical algorithm can be developed that will estimate the microwave loss of dry material in a

1 mixed-waste stream as produced by the optical image analysis, compare it with the
2 measured loss, and evaluate the average moisture content of a volume of waste.

4 **2.5. Calculations**

5 To calculate the composition of each waste sample, the number of dots counted
6 for each component in each image was multiplied by the kg/dot as calculated previously,
7 to yield the mass (kg) of each component in each image. The sums of mass from each
8 image were then calculated to obtain the total weight of each component in the waste
9 sample, and were presented as weight-percentage composition (% w/w).

10 The biogenic carbon, GCV and NCV were calculated for each of the waste
11 samples from the determined composition using the weighted percentages. Subsequently,
12 the GCV and NCV from the biogenic fraction (GCV_{bio} and NCV_{bio}) were determined,
13 also using weighted averages.

14 The NCV at different moisture levels was calculated by rearranging the formula
15 provided in the standard method (British Standards Institute, 2011a), as shown in
16 Equation 6:

$$18 \quad Q_{p,net,m} = \{q_{v,gr,d} - 212.2 \times w(H)_d - 0.8[w(O)_d + w(N)_d]\} \times (1 \times 0.01M) - 24.43M \quad (6)$$

19
20 Where $Q_{p,net,m}$ is the NCV at constant pressure with moisture content (M), $q_{v,gr,d}$ is
21 GCV at constant volume on a dry basis. The hydrogen, oxygen and nitrogen content of
22 the moisture-free sample are shown as $w(H/O/N)_d$.

By combining the elements in the curly brackets, a constant (k) was calculated for each component relating to the elemental content. This essentially assumes that the H, O and N content of each component remains consistent, however a previous study by Chester *et al* (2008) demonstrated that the variation between the chemical composition of waste components to be small (Chester et al., 2008). The equation was then adapted accordingly to allow the calculation of NCV at specified moisture content, as shown in Equation 7.

$$Q_{p,net,m} = (q_{v,gr,d} + k) \times (1 \times 0.01M) - 24.43M \quad (7)$$

The NCV at specified moisture content could then be calculated, demonstrating how the moisture content measurements described previously would be applicable in practice.

The energy from the biogenic fraction was calculated using the guideline method from the Office for Gas and Electricity Markets [OFGEM] (Ofgem, 2011). However, this guidance uses the assumed biogenic fractions as associated with the hand-sorting method (British standards Institute, 2011c), meaning that waste fractions are 100% biogenic (i.e. paper, card, wood etc.), 80% biogenic (leather and rubber), 50% (fabrics) and 0% for plastics. These values are not accurate, and do not agree with laboratory results published elsewhere (Fellner and Rechberger, 2009). Therefore, in this study the OFGEM guidance has been modified to calculate the percentage biogenic energy from the actual ^{14}C data for each waste component, which means that it is possible that certain proportions of the energy from inherently biogenic materials (i.e. wood) is discounted.

1 The biogenic fractions of the waste components generally vary based on the age
2 of the material. As a part of the carbon cycle, ^{14}C is produced in the atmosphere (Marley
3 et al., 2009) and can remain in the atmosphere for a significant period of time prior to
4 uptake from biomass material. The half-life of ^{14}C is 5,730 years (European Committee
5 for Standardisation, 2007; Marley et al., 2009), and so the biogenic content of wood,
6 garden waste and paper is lower than 100% due to the partial decay of ^{14}C . Measured
7 biogenic carbon content of wood-derived materials can be explained if the wood was
8 sourced from a relatively old tree; the wood was taken from the centre-rings of a long-
9 lived tree or if the wood was partially contaminated with petrochemical components
10 (paint, oils or varnish). The biogenic content of card was higher than that of paper and
11 wood, despite also being of woody origin. This is likely to be due to the card being
12 produced from much younger woodlands, as occurs in practices of sustainable forestry. It
13 is also likely that the card used in this study was produced from virgin materials, whereas
14 the paper may have been recycled several times before. It is documented that the
15 precision of the ^{14}C technique is 2% relative standard deviation [RSD] for values between
16 10-100% biogenic carbon content (European Committee for Standardisation, 2007).

17 Plastic is of petrochemical origin, and so it would be expected that the biogenic
18 content would be 0%, however some biogenic material was measured. This could be an
19 error in the analysis as the precision of the ^{14}C technique is quoted as 5% relative
20 standard deviation [RSD] between for values of 0-10% biogenic carbon content
21 (European Committee for Standardisation, 2007). Otherwise, it is possible that a very
22 small proportion of the plastics used in this study were produced from bio-based
23 polymers (bio-plastics).

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The differences between the known mass of the waste components and their determined mass are due to the translation of dot count to weight. As a result, the conversion used requires careful consideration, as this error is likely to be more pronounced in waste samples of much greater depth where overlap and hidden components are expected. The impact of greater depth could be minimised by measuring the depth of the waste, or by controlling the depth by ensuring that the samples are more spread out and do not exceed a certain height. As a waste sampling tool, the image analysis method is not suitable in its current form for monitoring the mass of waste components. However, this method is evidently highly suited for measuring the percentage composition as shown by the very strong correlation.

3.3. Microwave image analysis

Utilising the microwave imaging system, samples of the supplied waste types were imaged on a mock conveyor, as shown in Figure 3.

>>>>>>>>>>Insert Figure 3<<<<<<<<<<<<

Figure 3. Mock conveyor belt set-up (a) samples ready to be analysed, (b) microwave image of dry samples, and (c) microwave image of wet samples. Lighter shades represent higher absorption.

Textile, wood, paper and plastic were measured before and after being sprayed with water, which increased the total weight of the four samples by 30%. The contrast in microwave images results from differential microwave absorption, higher absorption being displayed as white. In Figure 3b and 3c, the wood sample exhibits stronger absorption compared with the other three samples, due to its greater absorptivity,

thickness and density, and also due to some trapped moisture. However, after spraying with water the textile sample becomes the most highly absorbing as a result of its large water retention capacity. In contrast, in the wood, paper and plastic samples water remained on or close to the primary sprayed surface, with little moisture penetration into the body of the material, therefore producing a weaker effect on microwave absorption.

Moisture content of different materials was evaluated, the results being summarised in Table 3. The thickness of the water layer in the beam path was estimated by weighing the material before and after spraying and dividing the weight difference by the sample area. The microwave loss due to water was then measured as the difference in loss between dry and wet samples, and the thickness of the water layer was calculated from Equation 5.

>>>>>>>>>>Insert Table 3<<<<<<<<<<<<<<<<<

It is seen that in the case of fabric the moisture content measured from microwave loss agrees with that derived from weighing the material; the case of cardboard is borderline, in that the obtained value is similar to the uncertainty; whilst wood is below the detection threshold of the system.

The results in Table 3 demonstrate the feasibility of microwave moisture detection, as well as highlight the requirements for system performance and the detection limits. The present system, which has a loss measurement uncertainty of 0.2 dB is incapable of detecting a compound water layer of less than 0.05 mm. In an industrial environment additional measurement errors may arise from the deployment and operation of the system, and must be addressed by careful system design and data analysis.

Nevertheless, further development of the microwave imaging technology should enable the average moisture content to be measured with an accuracy of better than 10 %, offering a viable solution for the waste industry.

3.4. Renewable energy content

The renewable energy values, as a percentage of the total GCV and NCV, as calculated from the known composition of the waste samples and the composition determined by the image analysis method, are presented in Table 4.

>>>>>>>>>Insert Table 4<<<<<<<<<<<<

As shown in Table 4, the renewable GCV and NCV, as a percentage of the total (shown in Tables 1 and 2), calculated from the known composition and from the image analysis-derived composition, were lower for sample A than for sample B. This is due to the significantly greater proportion of dense plastic in sample A, which contributed to a large fraction of the total energy content but was only 1% biogenic from the ^{14}C analysis. The percentage renewable energy determined by image analysis was lower than values calculated from the known sample mixtures; however these are still very similar (within 5% of the actual values, as shown in Table 4).

It is important to understand the impact of the moisture content on the NCV, as whilst the overall moisture content of the sample is a key consideration, the moisture retention, or specific load, for each component varies (Velis et al., 2012). Therefore, the ability of the AutoHarvest system to monitor moisture content at multiple points is a key

characteristic of the proposed system. Using Equation 7, the NCV of each waste component used was calculated at a range of moisture content (Figure 4).

>>>>>>>>>>Figure 4<<<<<<<<<<<<<<

Figure 4. The NCV of each waste component at different moisture content (calculated from Equation 7).

As seen in Figure 4, the NCV falls with increasing moisture content. Notably, the decrease is steeper for plastic than for natural-source materials such as paper, textiles and wood. Nevertheless, even for the latter, the NCV decreases by a factor of 3 for a moisture content of around 60%. Figure 4 therefore highlights the strong negative impact of moisture on energy recovery.

The biogenic fraction of the prepared samples was higher than that of typical mixed wastes, as shown in a previous study (Fellner and Rechberger, 2009) where the average biogenic fraction of mixed household waste and mixed commercial wastes were 70.3 and 64.2% respectively. As the biogenic fraction of mixed wastes is reported to yield lower energy than the non-biogenic fractions due to the oxygenation of the Carbon within the fuel (Voong and Othen, 2007), the energy from the biogenic fraction will be lower than the biogenic proportion.

Whilst the recovery of recyclable materials such as paper, card, metals and plastics increases, there will be a remaining residual waste stream for the foreseeable future. As such, residual waste has an important role to play in the recovery of renewable

energy as EU member states strive towards the 20% of electricity generated from renewable sources by 2020. As the residual waste stream changes with time, due to the removal of recyclable materials, the composition as well as the total available volume will change. Further work is required to estimate the potential impacts of future recycling on the renewable energy content of residual wastes (MSW and C&I). Furthermore, consideration needs to be given to the future uptake of plastics derived from bio-based materials, which are becoming increasingly common as alternatives to fossil-based plastics (Eerhart et al., 2012).

The Cranfield-NPL system is suitable for thermal energy recovery systems such as combustion, gasification and pyrolysis. This system can (or may) certainly be of use at waste processing facilities which produce a refuse-derived fuel [RDF] /solid recovered fuel [SRF] as a commodity sold to a third party for use elsewhere. The properties of the product, in this case the % NCV_{bio} (i.e. the ROC eligibility), could be determined prior to dispatch, thus potentially enabling a more dynamic market for the material, with the specific grade and value of the SRF being known for each batch produced. Further investigation of the proposed system in a waste processing environment would be required to ascertain parameters such as the number of required samples, the conveyor belt speed and sample thickness control. A schematic for the proposed system in a waste processing environment is provided in Figure 5, indicating potential height sensors which would enable corrections on sample thickness.

>>>>>>>>>>Insert Figure 5<<<<<<<<<<<<

Figure 5. Schematic of proposed system on a conveyor belt.

The conversion of waste components to liquid and/or gaseous fuels (as with gasification and pyrolysis) is not as straightforward as regards the CV, as used in this study. Therefore further consideration would be required. Ofgem has recently suggested that a method of assessing energy produced from biomass-derived material by a gasification process can be adopted by measuring the ^{14}C ratio within CO_2 in the flue gas (Ofgem, 2011). This method is appropriate for combustion; however for gasification this may not be directly applicable.

4. Conclusions

The two image analysis tools presented each demonstrate the potential to be applied, combined in a single system, for estimating the renewable energy potential of mixed wastes in a thermal treatment facility. The proposed system would, however, only be applicable to conventional incineration/combustion processes due to the more complex chemical processes involved in advanced thermal conversion technologies such as gasification or pyrolysis.

Alternative applications would be for the determination of mixed waste composition as outlined in a previous study by Wagland *et al.* (2012), or for the certification of SRF prior to delivery to an end-user.

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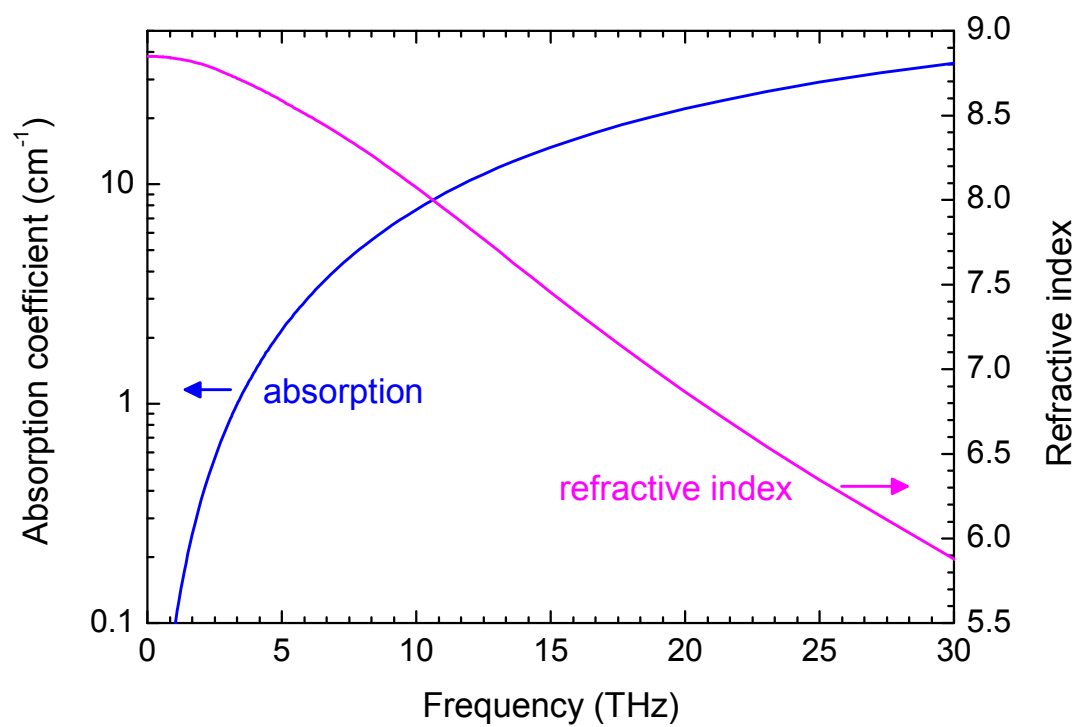
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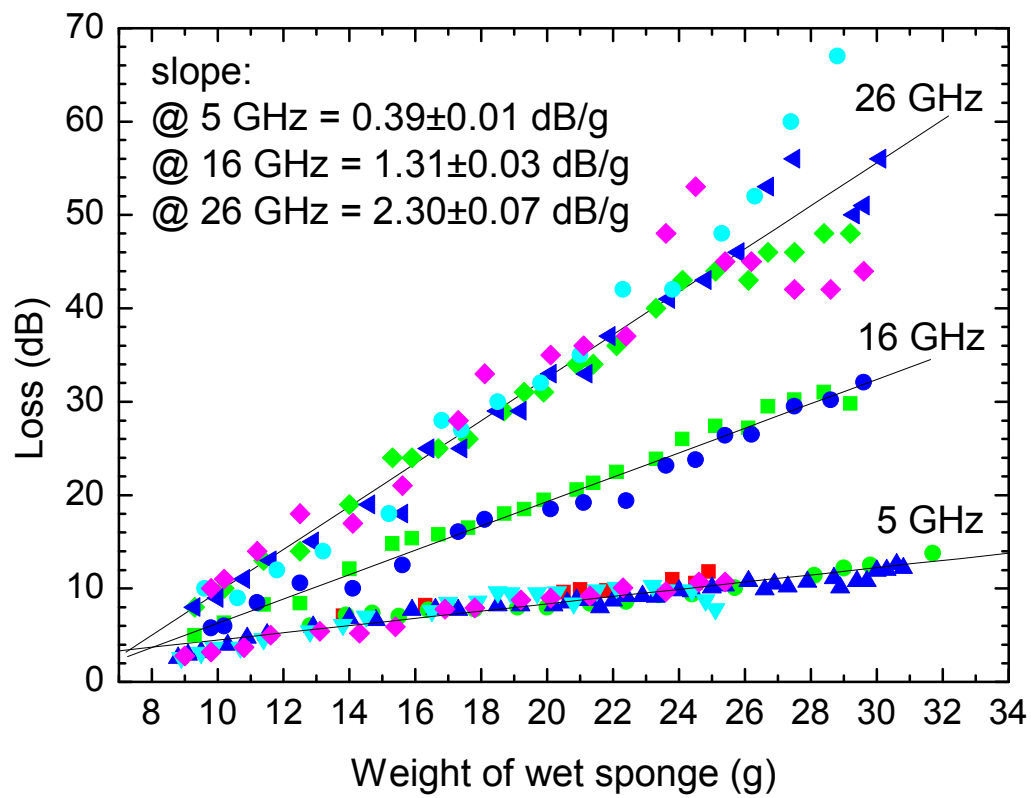
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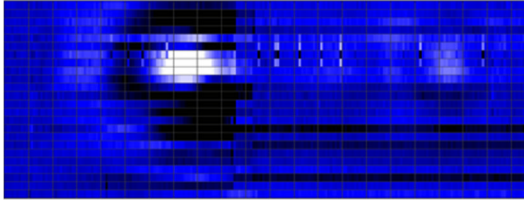
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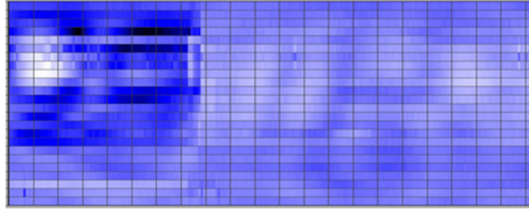




(a)



(b)



(c)

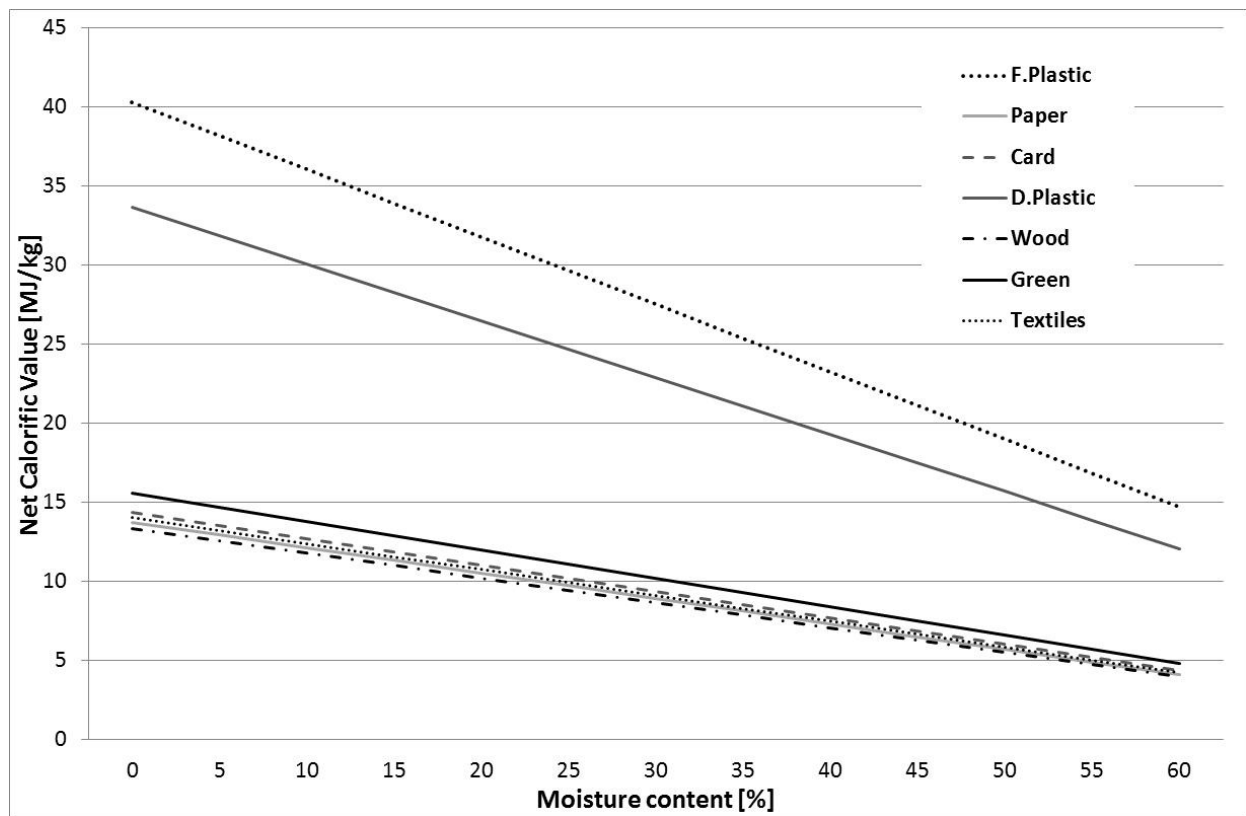
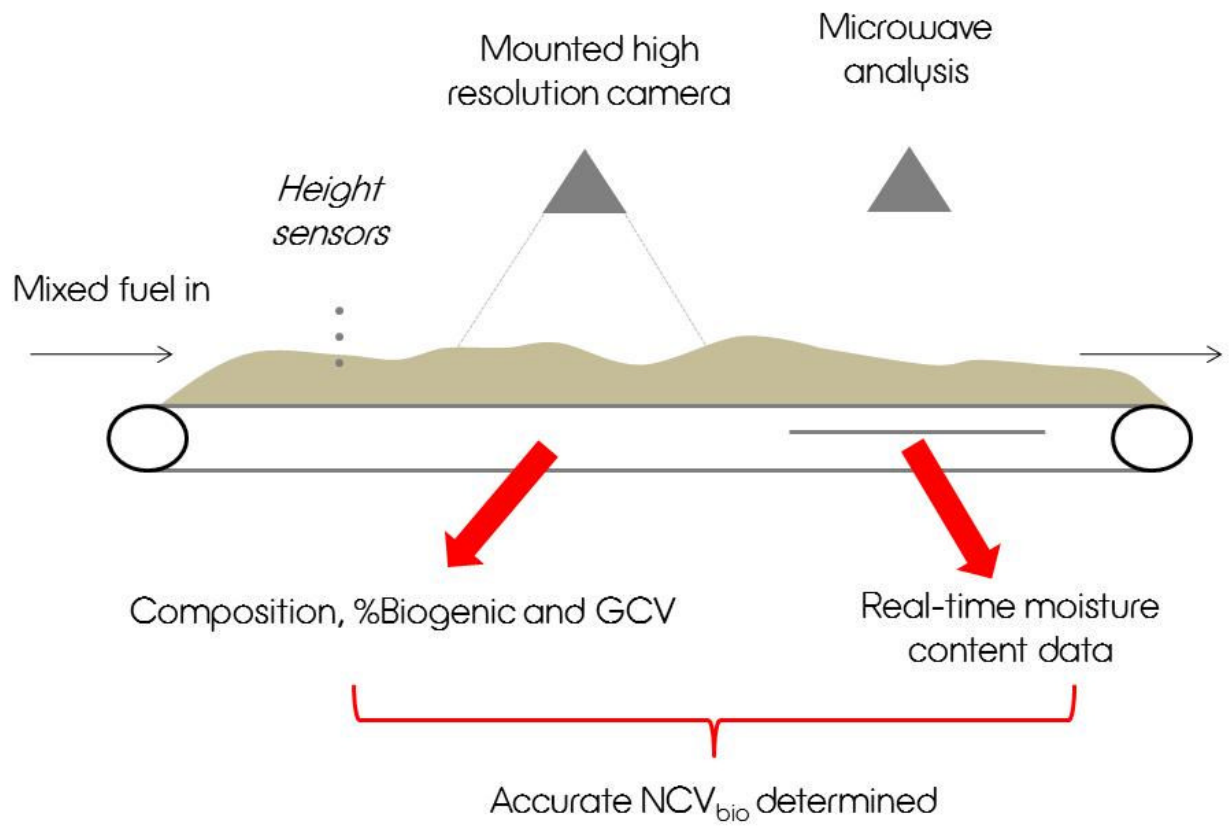


Figure 5



Component	Weight (kg)		% Composition		Ash (%)	Moisture (%)	Gross CV [MJ/kg]	Net CV [MJ/kg]	Biogenic C (%)
	A	B	A	B					
Paper	11.9	17.5	27.9	38.5	0.3	7.2	13,500	12,600	94
Card	12.9	3.6	30.2	7.9	1.2	13.9	13,000	12,100	100
D.Plastic	4.6	1.4	10.8	3.1	0.1	1.6	29,200	27,200	1
F.Plastic	-	0.5	-	1.1	5.4	2.9	41,300	39,100	1
Metal	1.0	1.8	2.3	4.0	-	-	-	-	-
Garden waste	3.4	4.5	8.0	9.8	2.3	25.8	11,800	11,000	96
Textiles	2.2	-	5.2	-	3	6.2	14,000	13,000	86
Wood	6.7	4.2	15.7	9.2	2.4	9.8	13,200	12,300	90
Inert	-	12	-	26.4	-	-	-	-	-
Total	42.7	45.5							

Table 1. Proximate, calorific, ^{14}C and composition data for mixed waste materials.

Component	Weight (kg)		% Composition	
	A	B	A	B
Paper	19.6	23.4	25.7	38.9
Card	20.9	5.4	27.4	9.0
D.Plastic	10.0	1.8	13.1	2.9
F.Plastic	-	0.8	-	1.3
Metal	2.1	2.2	2.8	3.7
Garden waste	6.7	4.1	8.8	6.8
Textiles	4.1	-	5.4	-
Wood	12.9	3.8	16.9	6.3
Inert	-	18.7	-	31.0
Total	76.4	60.2		
Correlation (r)	0.992	0.988	0.993	0.988

Table 2. Component weight and % composition determined by image analysis

Material	Thickness of water layer (mm)	Loss when dry (dB)	Loss when wet (dB)	Loss due to water (dB)	Calculated thickness of water (mm)
Wood	0.006±0.001	3.5±0.2	3.6±0.2	0.1±0.3	0.02±0.08
Cardboard	0.033±0.002	0.1±0.2	0.3±0.2	0.2±0.3	0.05±0.08
Fabric	0.33±0.01	0.3±0.2	1.6±0.2	1.3±0.3	0.31±0.07

Table 3. Moisture content of different materials calculated from microwave loss.

		Renewable gross CV [MJ/kg]	Renewable net CV [MJ/kg]
Component	Paper	12,700	11,800
	Card	13,000	12,100
	D.Plastic	292	272
	F.Plastic	413	391
	Metal	-	-
	Garden waste	11,300	10,500
	Textiles	12,000	11,200
	Wood	11,900	11,100
	Inert	-	-
% Renewable energy	Sample A	74.69	74.69
	Image analysis Sample A	70.72	70.71
	Sample B	80.25	80.09
	Image analysis Sample B	79.61	79.44

Table 4. % renewable energy from each waste sample, determined from the known composition and from image analysis. CVs quoted on an ‘as received’ basis.



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