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Lowering Costs by Improving Efficiencies in Biomass Fueled Boilers: New Materials and Coatings to Reduce Corrosion

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Executive Summary

One of the technologies aimed at producing an energy source that is carbon neutral; cost effective with security of supply is biomass combustion to generate either or both heat and power. One of the main issues of biomass from an operational view is the corrosive nature of the combustion products and the variable nature of these products depending on the biomass source.

To counteract the corrosive threat to the integrity of the plant corrosion resistant coating can be applied to the surface areas of the plant that are at most risk. Coating have been used in biomass and waste to energy plant for over 20 years with reasonable success but in order to achieve a commercial life of the plant the operating conditions are maintained significantly lower than those for pulverised coal plant. The aim of the BELENUS project is to investigate the effectiveness of a number of coatings to protect the substrate materials against the corrosive biomass combustion products at higher operating temperatures than previous experienced, i.e. up to 650°C where current plant operate at or below 540°C.

Due to the large range of biomass fuels available it is necessary to select some representative fuels for use in the BELENUS project to allow sufficient experimental time to evaluate a number of coating/substrate combinations. One of the purposes of Work Package 1 is to select suitable fuels for use within the BELENUS project. A survey has been conducted of the various biomass fuels and 3 generic types have been identified as being of sufficient commercial interest, i.e. sufficient quantities available for plant operation, and with combustion products that offer challenging environment in which to trial the candidate coatings.

The 3 fuels identified for use within the BELENUS project are agricultural straw to be sourced from Spain; forestry residue to be sourced from Scotland and waste industrial wood to be sourced from England. The agricultural straw usually contains high amounts of K and Cl, which reacts with Si and S leading to liquid or solid ash deposits and is considered to be a mid-range corrosive fuel type and will probably be selected for the initial round robin tests of the candidate coatings. The forestry residues fuel selected is that used commercially in the Steven's Croft bubbling fluidised bed boiler, in southern Scotland, which usually has high metal and chlorine content but considered the more benign of the biomass fuels in terms of corrosion. The industrial waste wood selected is that used in the Blackburn Meadows bubbling fluidised bed fired power plant located in central England and contains high amount of Cl, alkali and heavy metals, leading to potential severe corrosion problems in boilers.

All 3 fuel sources have been analysed for combustion species and ash products so that in the laboratory screening tests environments similar to those found in the plant can be simulated. The analysis of the 3 fuels are presented in this report along with an indication of the variability of species and ash products found in the 2 commercial plants that are targeted for full scale demonstration under Work Package 7.

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1. Introduction

One of the main factors driving energy policy is climate change, and in this respect, the utilisation of coal as a fuel for power generation is becoming increasingly controversial. The concern about increasing greenhouse gas (GHG) emissions has given rise to several directives such as the Large Combustion Plant Directive (European Commission, 2016) and the Kyoto Protocol (United Nations Climate Change, 2019). This has led to national initiatives to reduce the use of coal, for example, the closure of many coal-fired plants in the United Kingdom (Toporov, 2014); the decline of coal utilisation in the United States (Mooney and Dennis, 2019), and mounting pressure on companies to divest from coal in France (Baxter et al., 2018).

Reports from the 2018 World Energy Outlook predicts a 3.7% compound annual decline in the global thermal coal trade (Roker, 2018a). The International Energy Agency (IEA), in its 'sustainable development scenario' cited by Roker (2018a), forecasts an 80% decrease in coal consumption in the global power sector, down to 732 million tonnes in 2040 (Roker, 2018a). In some emerging economies priority has been given to expansion of new coal builds to match the growing energy demands (e.g. China, Brazil, India, Indonesia, Mexico, South Africa) (Power Technology, 2017; International Energy Agency, 2018a). As examples of the high usage of coal are India's 60% of electricity produced from coal, and South Africa's 82% of electricity generated from coal (IEA, 2018b).

There are different approaches to reduce carbon dioxide emissions, such as co-firing coal with biomass or a complete switch to renewables and other sustainable fuels (Simms, 2011b). Biomass combustion is gradually gaining popularity as an alternative to coal-firing, where the range of biomass fuel species employed as fuel for power generation includes wood pellets, olive cake and pellets, palm kernel expellers, citrus pulp expellers, sunflower husk, sawdust, energy crops (e.g. willow, poplar, miscanthus, straws and grasses) and sewage sludge (Vassilev et al., 2010; The Biomass Energy Centre, 2011).

Biomass is regarded as inherently low carbon given that plants absorb an amount of carbon equivalent to that released to the atmosphere when biomass fuels are burnt (The National Council for Air and Stream Improvement, 2015). Biomass, however, is less energy dense than coal and would require a significant land mass to grow the amount needed to replace coal completely. As an example, the Department of Energy's (DOE) 2016 billion-ton model (BT16) (Langholtz et al., 2016) states that for the commercialisation of biomass to energy crops, the maximum eligible pastureland required is about 47 million acres (or 11% of pastureland). More specifically, a report from Partnership for Policy Integrity (2016), citing the aforementioned DOE's billion-ton model, states that forest harvesting will require clear-cutting up to 4.7 million acres per year to produce a 100 million dry tons of (forest) biomass for the production of wood pellets.

Biomass is a multifarious term covering a range of solid organic products, and to a lesser extent, inorganic matter, generated from natural and anthropogenic processes (Vassilev et al., 2015). One way of classifying is by grouping into six groups based on the structure of the organic and inorganic constituent (Vassilev et al., 2010; The Biomass Energy Centre, 2011; Hustad and Barrio, 2015):

- Agricultural residues (from crops, food processing and animals).
- Biomass mixtures.
- Dedicated energy crops (high yield crops are grown specifically for energy applications).
- Industrial waste and co-products.
- Municipal waste/food waste.
- Wood residues (from forest residues, wood processing, arboriculture activities, and the paper and furniture industry).

All solid biomass is made up of three main components: cellulose, hemicellulose and lignin. The organic part of biomass (mainly C, H, N and O) is present in the molecular structure of the cellulose, hemicellulose, and lignin component of biomass matter. The inorganic matter (0.1 – 46 wt.% on a dry basis) is made up of various minor species from different mineral groups and classes such as phosphates, carbonates, silicates, chlorides, sulphates, oxyhydroxides, nitrates; as well as some amorphous inorganic phases (Vassilev et al., 2010, 2013).

Although the literature on the chemical composition of different biomass varieties reveals similar contents of C, H and O (dry ash fuel basis), there are significant differences in the contents of N, ash-forming elements, and moisture. For instance, the wood-derived fuels show lower values of ash, Cl, K, N, S and Si, and higher concentrations of C and Ca. Straws and grasses, on the other hand, have a relatively high level of Cl, K, N, S, Na, S and Si (Vassilev et al., 2010). Si and Cl content is high in herbaceous biomass relative to other classes of biomass fuels (Jenkins et al., 1998). The agricultural derived and contaminated biomass group shows the most significant difference in levels of ash, moisture, C, Cl, H, Na, N, S and occasionally Al, Fe, P and Ti. These distinctions are a result of their original geographic location and handling process (pesticides, harvesting and storage) (Vassilev et al., 2010).

The alkali and alkaline earth metals in biomass fuels are very volatile and thus easily released at combustion temperatures (Hurley et al., 1993; Jenkins et al., 1998). Also, Cl facilitates the mobility of many compounds, especially K which is present in the form of water-soluble inorganic salts which can easily volatilise during combustion; thus the tendency for fouling of boiler tubing may increase in biomass combustion (E.ON UK, 2004; Shao et al., 2012). The implication is that, during combustion, these species are released into the flue gas and interact with the boiler components and almost always result in erosion, deposition or/and corrosion of superheater/reheaters (Wright et al., 1997), thus creating significant maintenance issues in industrial steam raising boilers.

Fireside corrosion of evaporator, superheater and reheater components is more challenging in boilers burning pure biomass than for coal-fired boilers, as the flue gas contains corrosive gases, high concentrations of low melting alkali metals and chlorides that severely damage and reduce the life of boiler tube materials. Hence steam conditions in biomass-fired plants are generally lower than those of coal-fired plants if the boiler must continue its operation over an extended period (Simms, 2011a).

Sulphur plays a crucial role in the fireside corrosion mechanism. During combustion, pyrite (FeS_2) burns to form SO_2 and FeO which can be further oxidised to SO_3 in the flue gas as it cools. Laboratory experiments have revealed that higher SO_3 partial pressures can be generated by catalytic oxidation of SO_2 beneath the tube deposits hence ensuring the stability of complex sulphates up to 700°C (Wright and Shingledecker, 2015). Fireside corrosion studies reveal that the rate of dissolution of the protective scale increases when the local partial pressures of SO_3 in flue gas increases from 1000 ppm to 5000 ppm (Wright et al., 1997). However, if the metal temperature is raised above the decomposition temperature for iron sulphate, the molten sulphate layer ceases to exist, and the corrosion rate drops (Weele, 1991), as shown schematically below.

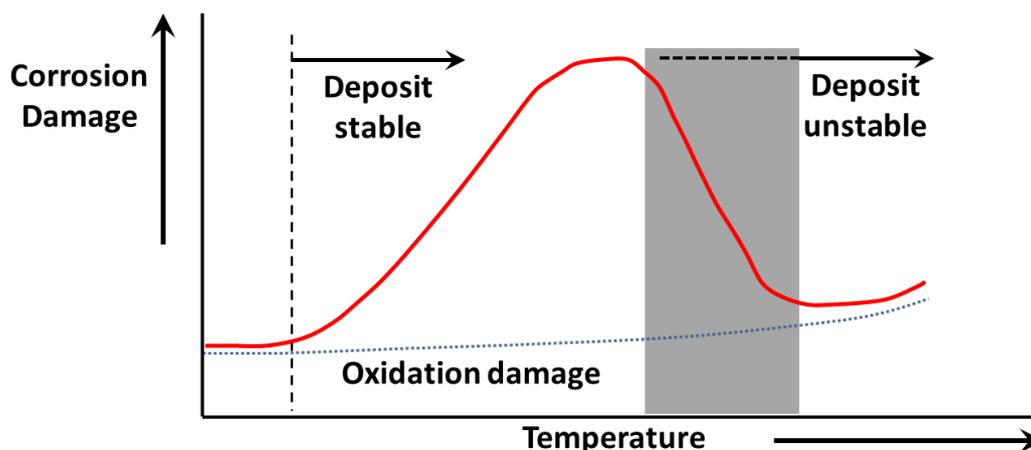
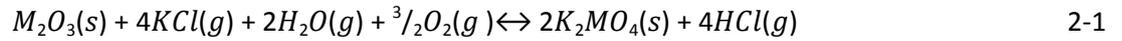


Figure 1. Effect of metal temperature on the fireside corrosion rate.

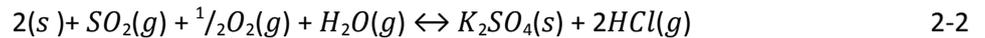
Although it is generally accepted that high Cl fuels may speed up the fireside corrosion process, it has been difficult to predict the degree to which the Cl content contributes to fireside corrosion. In biomass combustion,

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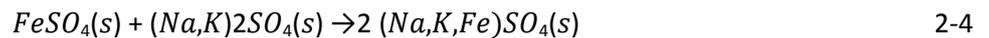
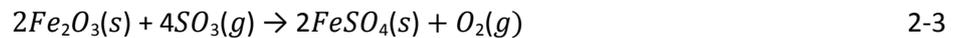
different mechanisms are observed particularly when burning low S biomass fuels (Cl attack), as the fireside corrosion is mainly attributed to alkali chloride deposits (Shao et al., 2012; Okoro et al., 2017). Deposition of the alkali chloride occurs via condensation mechanism, which is driven by the temperature difference between the gas and the boiler tubes (superheaters/reheaters) (Uniper Technologies, 2016). The KCl in the deposit can react with the oxide of the alloy elements (equation 2-1) (Okoro et al., 2017) or with the gaseous species in the gas stream (equation 2-2) (Okoro et al., 2017).



Where M = oxide of the alloying element



Biomass contains more water-soluble K but lower amounts of S and Na when compared to coal. If the furnace temperature is high enough, K can be released into the combustion gas (Hurley et al., 1993). If the alkali content is high, this could lead to the deposition of alkali sulphate ((Na/K)2SO₄) which could form a low-melting point compound with another species, e.g. Fe₂O₃, on the oxide scale on the tube surface or from the ash which melts at 560 °C (Weele, 1991) (equations 2-3 and 2-4).



As heat is being transferred from the gas to the working fluid in the heat exchangers, the flue gases are cooled and, subsequently, alkali metal sulphates (Na₂SO₄, K₂SO₄) form in the furnace and condenses on the tube surface (Simms et al., 2007; Lant et al., 2010; Wright and Shingledecker, 2015). The alkali compounds can be deposited via direct condensation on the tube surface, or impaction of fly ash particles carrying the condensed alkali, or by thermophoresis of smaller particles (Wright and Krause, 1997). These deposits will eventually grow to the extent that they insulate the tube surface from the gas stream thereby impeding heat transfer to the tubes (Hurley et al., 1993). Above 580 °C, and in the presence of SO₃, the mixed deposits become molten at the tube surface, react with another constituent of the deposit and form a layer of highly corrosive alkali iron trisulphate mixture (2Na₃Fe(SO₄)₃) beneath the ash deposit. The molten alkali iron sulphate dissolves the protective oxide scale thereby causing accelerated oxidation and sulphidation (Wright and Krause, 1997).

In order to mitigate the effects of biomass derived corrosion species the Belenus projects aims to expose a number of superheater and reheater materials with protective coatings in some representative biomass environments. From the 6 biomass types listed above 3 types with potential large scale commercial application have been selected for evaluation within the Belenus project. Representative samples from Agricultural Waste, Industrial Waste and Wood Residues will be analysed for their combustion gases and residues to allow coated samples to be laboratory pilot scale tested in simulated biomass environments. The most promising coatings will be down selected for exposure in commercial plant as part of work package 7 of this project. This report provides some details of the biomass fuels to be used within this project.

2. Results and Discussion

Biomass fuels have in recent years been categorised and traded under a number of standards and schemes. In addition to the descriptions and standards described below, it should also be recognised that for a biomass material to be considered as fuel for commercial scale power plant applications, i.e. plants that have rated outputs of ~10MWe or greater, the biomass must be available in sufficiently large quantities to enable the plants to operate continuously. In practise, this means thousands of tonnes per year must be readily and reliably sourced then transported economically to the power plant.

The international standard ISO17225, Solid biofuels – Fuel specifications and classes, was first issued in 2014. Part -1 describes general requirements of solid biofuels, part 2 describes the requirements for graded wood pellets with part 4 describing the requirements for graded wood chip.

Within this standard solid biomass fuels are primarily classified under one of five headings based on the biofuel origin and source as below:

- a) Woody Biomass;
- b) Herbaceous Biomass;
- c) Fruit Biomass;
- d) Aquatic Biomass;
- e) Blends and Mixtures.

Woody biomass is derived from trees, bushes and shrubs. Herbaceous biomass comes from plants having non-woody stems and die back at the end of the growing season. Fruit biomass comprises those parts of a plant which are from or hold seeds. Aquatic biomass is derived from plants adapted to live in water / aquatic environments. Blends are materials comprising intentionally mixed biofuels, whereas mixtures are formed from unintentionally mixed biomass fuels. A second level of classifications describes whether the biomass is a virgin material, a by-product or residue or, in the case of woody fuels, previously used. Further sub-groups define in greater detail the breakdown of the material type, for example in the case of woody fuels, whole trees with or without roots, stem wood, logging residues, stumps / roots, and may include the type of woody material, for example broadleaf, coniferous, short rotation coppice, bushes. For herbaceous biomass the second category describes whether the material is derived from agriculture / horticulture or is a by-product or residue from the food or herbaceous processing industries.

Part 2 of the standard, describing graded wood pellets has established distinct technical quality standards for pellets in residential/commercial applications and industrial applications. The standard defines wood pellet requirements in terms of moisture, energy density, abrasion resistance, particle size and shape. They have enabled a trade code for wood pellets to be established so that wood pellet trade flows are now covered in official trade statistics (Thraen et al., 2017).

For several years, operators of large scale (>100MWe) pulverised fuel fired utility boiler plant have been purchasing wood pellets according to the “Initiative Wood Pellets Buyers: Industrial wood pellets specifications”, using the I2 Industrial specification. This requires the wood to be sustainably sourced from forest, plantation and other virgin wood and chemically untreated wood residues, falling within the categories 1.1 and 1.2.1 of EN14961-1, which also defines limitations as in ISO17225, with the further concentration limits on the elements Cl, N and S, together with limits on heavy metal contents.

ISO17225-4 Solid Biofuels - Fuel Specifications and Classes - Graded wood chips, describes the requirements for wood chip fuel as may be fired in fluidised bed and grate fired boilers and is primarily directed to residential, small commercial and public building applications. As well as specifications for size, ash, moisture and bulk density, the materials are divided into grades A1 and A2, plus B1 and B2. A1 represents virgin woods and chemically untreated wood residues having the lowest ash contents indicating little or no bark content and low moisture contents. Whilst A2 is from the same sources it may have higher ash and moisture content. B1 extends the origin and source to include other material such as Short Rotation Coppice (SRC), wood from gardens and

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plantations, etc. and chemically untreated industrial by products and residues. Grade B2 further includes chemically treated industrial by-products and residues and chemically untreated used wood, and provides that this does not include heavy metals or halogenated organic compounds. Limits for N, S and Cl, together with heavy metals are not specified for Grade A wood chip but are specified for Grade B.

In addition to Grades A and B, larger scale boilers frequently fire Grade C wood as described in the standard EN 15359 – Solid Recovered Fuel (SRF) and include materials treated with halogenated organic compounds. The burning of Grade C wood fuel must be undertaken within boilers that are Waste Incineration Directive (WID) compliant. Demolition wood is categorised as Grade C owing to the difficulties in fully characterising the material. The final Grade D category describes wood that has been treated with heavy metal preservatives and is considered a hazardous waste.

The classifications within the ISO17225 standard do not extend to other more challenging solid waste fuels such as Solid Recovered Fuels (SRF), Meat and Bone Meal (MBM), food wastes etc.

A useful reference source for the characteristics of a range of fuels including woody and herbaceous materials is the BIODAT or Phyllis2 database, this being the successor to the earlier Phyllis database and the result of work conducted by PHYDADES Project. The CEN/TS 14961 classification is a technical specification published in 2005 by the working group CEN TC335 solid biofuels. It divides solid biomass into three main groups (woody biomass, herbaceous biomass, and fruit biomass). These groups are subdivided in two further levels. The database individual records contain variable quantities of information dependent upon the sources of the information and may include proximate and ultimate analysis together with biochemical analysis and chemical analyses of major and minor elements.

In 2010, the technical specification was followed by the European Norm EN14961-1 (“General requirements”) and in 2011 by EN14961-5 (“Firewood for non-industrial use”). The subdivision used in these norms differs slightly from CEN/TS14961.

The ECN classification is an evolving scheme based on a mixture of plant physiology and practical considerations. Materials are divided into groups that are in turn divided into subgroups. In May 2003 several group names were adapted and subgroups were added or subdivided, mainly to reduce the number of "other" materials.

The major classifications are:

Untreated wood:

The “untreated wood” group contains fresh wood, park wood waste and wood from saw mills. Several individual tree species, such as willow, are separate subgroups. For other trees a division is made in tropical and other hardwood (trees with leaves) and softwood (trees with needles). If an overview of all hardwood data is needed one should select the subgroups beech, birch, oak, poplar, willow, tropical and other hard wood. Park wood waste is considered an untreated subgroup but in general information on the type of tree species is lacking. The subgroup others contain data records of unspecified untreated wood samples. Bark, cork, leaves and needles form separate subgroups.

Treated wood:

The group “treated wood” contains composted wood (wood after being used in a composting process), demolition wood, preserved wood (treated with preservatives like chromated copper arsenate or creosote) and particle board. If a treated wood stream contains a mixture of the above mentioned types it can be found in the subgroup others.

Straw:

From plant physiological point of view, the difference between straw and grass is not always straightforward. Here the commonly used definition of straw (from grains like wheat, barley, rice and maize) is used. In May 2003, rape, rye, sorghum and sunflower have been moved from the subgroup others to separate subgroups. The subgroups others contain straw from other plants like oats and beans, straw mixtures and unspecified straw.

Grass/plant:

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Different grass-like species can be found in separate subgroups of the group grass. Verge grass is a mixture of different (unidentified) grass species. The subgroup hemp has been moved from straw to grass and new subgroups have been created for jute and kenaf. These species are important sources of fibres. New subgroups (fruit, vegetables and flowers/garden plants) contain materials previously collected in others or in other organic residue.

Husk/shell/pit:

In the group husks/shells one can find the outer parts of different nuts, like cacao-shells. The group name has been extended to include pits. This prevents ambiguity for waste materials from the olive industry. Previously, some of these materials were to be found in other organic residue, subgroup food industry.

Other organic residues, manure, sludge:

The group "other organic residues" now includes products. It contains a number of plant-based materials, such as new and waste paper, residues from agriculture and horticulture, residues and products from the food industry, the organic fraction from domestic waste and auction waste. Also textile waste is a subgroup in that group, although in some cases it can contain fossil fuel based materials. Manure, also an organic residue, can be found as a separate group in the database. The group "sludge" is divided in sludge from sewage water treatment, sludge from the paper industry, waste water treatment, sludge from culverts and sludge from the food processing industry.

MSW and RDF:

Municipal Solid Waste (MSW) and Refuse Derived Fuel (RDF) are clustered in one group, whereas the separated organic fraction from MSW (separately collected in the Netherlands) can be found in the group "other organic residues".

Non-organic residues:

The group "non-organic residue" contains waste streams which consist mainly of fossil fuel based materials, like electronic scrap, automobile shredder residues and cable waste. Although some forms of carpet waste consist mainly of natural materials, it has been decided for reasons of clarity to place it in that group. In the subgroup plastics analysis data of individual plastics can be found, whereas the subgroups others contains information on mixtures and, for instance, car-tyres.

Char:

The group "char" contains the solid remains after pyrolysis of a great variety of materials in subgroups named after the main group of the original material.

Algae:

The group "algae" with subgroup others contains aquatic photosynthetic organisms that lack true leaves, stems, roots and vascular systems characteristic of plants.

Torried material:

This group contains materials which have been given a thermal treatment at moderate temperature (around 200°C) to improve the fuel quality, e.g. grindability.

Fossil fuel:

Data of fossil fuels, including peat, are added as a reference in a separate group.

In terms of woody fuels, these are grouped into the following sub-categories:

Forest residue chips (pine / spruce), Bark, Pine Bark, Spruce Bark, Birch Bark, Willow, Eucalyptus, Markhamia, Sawdust, Stump Chips, Withered Leaves, Wood Pellete, Demolition Wood, Whole Chips (from whole trees), Forest Residue Chips, Pruning Wood, Felling Wood, Residual Wood, Wood Residue, Logging Residues, Thinning Wood, Poplar Leaf, Used Wood (chemically untreated – Grade / Class A), Used Wood (Chemically Treated – Grade / Class B) and Used Wood (Chemically treated (Grade / Class C).

Used wood, chemically treated (class D) is not included in Phyllis database as it is considered a hazardous waste rather than a biofuel.

2.1. Agricultural Straw

The agricultural sector produces large amounts of residues utilisable for bioeconomic purposes. Among the different agricultural residues in the European Union, straw shows the highest potential, with approximately 95 Mt of lignocellulose feedstock (LCF), of which the most promising are wheat straw (46 Mt), barley straw (16 Mt) and rape seed straw (14 Mt). Currently, less than 8% of the theoretical potential of straw is recovered from fields (Thorenz et al, 2018). In Spain, the production of cereal straw amounts to 6 million tonnes (1000kg per sown area).

Harvesting residues of wheat grain (common wheat and durum wheat), corn grain, barley grain and rapeseed represent about three quarters of the annually accumulated lignocellulose residues from EU's fields. Wheat straw from common and durum wheat remains the most important agricultural lignocellulose residue in the European Union. The growth rate of the cultivated area is expected to stay rather small with an average annual growth of around 0.1 per cent (European Commission, 2017b). In countries with a long EU membership, yields tend to be on average higher than in countries with more recent EU accession (Wietschel et al, 2019).

Several reports have been published assessing the potential of straw in the energy sector (Lal et al, 2005; De Lucas et al, 2012]. Fifteen large combined heat and power plants (CHP) are operating in the EU (Thorenz et al, 2018), most of which are located in Denmark (i.e, Studstrup y Avedøre).

Among the different available agricultural residues, cereal straw has been selected for Belenus experiments as it is highly representative of Southern Europe. In Spain, there are three important combustion plants burning straw, totalling 61 MW, as shown in table below (De Lucas et al, 2012)). These are Sangüesa combustion plant (Navarra), operational since 2002, Briviesca (Burgos) and Miajadas (Cáceres), operational since September and November 2010, respectively. All of these plants are reference installations with regards to biomass development for electricity generation in the south of Europe. These 3 plants process a total of 400.000 tons annually of cereal straw and other agricultural residues to generate enough electricity to supply 140.000 homes, without increasing CO₂ emissions.

Table 1. Data of the most important combustion plants burning straw in Spain.

	Miajadas	Briviesca	Sangüesa
Location	Cáceres	Burgos	Navarra
Capacity	16 MW	16 MW	25 MW
Raw material	110.000 t/year	102.000 t/year	160.000 t/year
Employment (direct/ indirect)	100/75	25/70	100
Setting up	2010	2010	2002
Promoter	ACCIONA	ACCIONA Y EREN	ACCIONA

Scarlat et al. (2015) show their straw demand based on the low heating value (LHV) of straw dry matter, which is 17.5 MJ/kg. Straw burning in combined heat and power plants is a growing field. This analysis neglects small plants for household heat production, as well as the co-firing of straw in coal-fired power plants, due to the lack of reliable data.

Apart from the economic and environmental advantages of employing an agricultural residue, the chemical composition of straw will provide us with a more aggressive atmosphere during the combustion experiments, which is required for BELENUS purpose, as consequence of the typical high alkali and chlorine content which may increase deposits formation and corrosion processes. In this sense, wheat and barley straw samples (from Spain) have been selected for the first combustion experiments. Fuels properties (including proximate and ultimate analyses as well as the calorific values) have been determined for these biomasses at CIEMAT laboratories and are tabulated below. Further chemical analyses are being developed for halides and major elements determination, the results of which are included below.

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Table 2. Analyses of wheat straw and barley straw samples.

		Units	Wheat straw	Barley straw
As Received Analysis	Moisture	%	8.3	7.2
	Volatiles	%	69.5	73.2
	Fixed Carbon	%	17.3	15.4
	Ash	%	4.9	4.2
	Calorific Value (Higher Heating Value)	kcal / kg	3934	3996
	Carbon	%	41,8	42,6
	Hydrogen	%	6,4	6,3
	Nitrogen	%	0,56	0,72
	Sulphur	%	0,11	0,11
Net	Calorific Value (Lower Heating Value)	MJ / kg	14.0	14.9
Dry Analysis	Ash	%	5.3	4.5
	Calorific Value	MJ / kg	15.9	16.1
Dry Ash Free Analysis	Volatiles	%	80.1	82.6
	Calorific Value	MJ / kg	16.8	16.8
	Hydrogen	%	7.4	7.1

2.2. Forestry Residues

Forestry residues are widely available and used as a source for power plant fuels across many countries in Europe and worldwide. Many of these fuels are derived from quick growing wood species such as pine or increasingly in the future eucalyptus, or, in countries at higher latitudes, include species such as birch. The different species and the locations in which they are grown determine the wood composition and affect the content and type of undesirable ash forming species. Relatively quick growing woods such as Eucalyptus can prove more challenging to fire in boilers due to slightly increased chlorine contents compared with species such as birch or pine.

Given the target of the Belenus project to reduce the effects of boiler fireside corrosion, Eucalyptus was initially selected as the most appropriate forestry residue fuel to provide a challenging combustion environment in which to test and operate. However, Eucalyptus wood is still not commonly available in sufficiently large quantities to fire in commercial boilers. Instead, another challenging forestry residue has been suggested and provisionally selected as the fuel to be examined. The suggested fuel is based on pine grown in southern Scotland and has been used in commercial boilers for approximately the last decade. The Steven's Croft bubbling fluidised bed boiler located in southern Scotland, owned and operated by E.ON, fires this forestry waste, blended with a small proportion (<15%) of recycled wood fibre, the latter sourced primarily from recycled wooden furniture / cabinets, i.e. chipboard and Medium Density Fibreboard (MDF). The combination of recycled fibre and the local forestry industry operating in a region called the lead hills, means that the fuel contains enhanced levels of the heavy metals Zn and Pb compared to many other forestry residues. Typical analysis for the fuel can be seen in the tables below.

Table 3. Typical Fuel Analysis for the Forestry Residue and Recycled Wood Fired Blend.

		Units	Max	Mean	Min
As Received Analysis	Moisture	%	58.0	46.8	29.1
	Volatiles	%	55.8	41.8	33.7
	Fixed Carbon	%	13.0	9.1	6.6
	Ash	%	9.8	2.3	0.3
	Calorific Value (Higher Heating Value)	kJ / kg	13980	10400	8440
	Sulphur	%	0.06	0.02	0.01
	Chlorine	%	0.20	0.04	0.01
	Hydrogen	%	3.96	2.97	2.40

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Net	Calorific Value (Lower Heating Value)	kJ / kg	12420	8616.79	6500
Dry Analysis	Ash	%	17.8	4.3	0.6
	Calorific Value	kJ / kg	20324	19553	17219
Dry Ash Free Analysis	Volatiles	%	85.7	82.2	79.4
	Calorific Value	kJ / kg	20980	20443	20130
	Hydrogen	%	6.1	5.8	5.7

Table 4. Mean and Range of Monthly Composite Ash Analyses for the Forestry Residue and Recycled Wood Fired Blend.

Elements	Units	Max	Mean	Min
Al	mg/Kg	3694	1485	540
Co	mg/Kg	10.2	3.1	1.1
Cr	mg/Kg	68.3	17.4	4.5
Cu	mg/Kg	110.0	30.4	4.4
K	mg/Kg	2532	1336	724
Mn	mg/Kg	434	166	59
Na	mg/Kg	2955	899	313
Ni	mg/Kg	11.2	3.8	1.1
Pb	mg/Kg	423	163	49
Sn	mg/Kg	16.5	4.1	0.4
Tl	mg/Kg	15.1	2.9	0.9
V	mg/Kg	6.0	2.3	0.7
Zn	mg/Kg	2696	243	29
As (as hydride)	mg/Kg	29.8	9.0	1.3
Sb (as hydride)	mg/Kg	21.7	5.9	1.2
Cd	mg/Kg	2.6	0.9	0.1
Hg	mg/Kg	0.130	0.035	0.004
F	mg/Kg	39.6	14.3	4.1
Br	mg/Kg	20.8	3.0	2.0
Al (metallic)	mg/Kg	805	152	43
Ash	w/o (dry)	9.6	4.6	1.7
Cl	w/o (dry)	0.12	0.09	0.06
Gross CV	MJ/Kg	11.0	10.3	9.4
Moisture	%	52.6	47.0	43.8
Net CV	MJ/Kg	9.2	8.4	7.5
S	w/o (dry)	0.06	0.04	0.02
Ash Oxide Matrix (Corrected for SO₃) (weight %)				
Al ₂ O ₃		21.74	8.26	4.99
BaO		1.12	0.60	0.17
CaO		32.48	24.45	16.35
Fe ₂ O ₃		9.72	5.10	3.12
K ₂ O		8.77	5.36	2.37
MgO		5.50	3.95	2.46
Mn ₃ O ₄		1.32	0.74	0.20
Na ₂ O		8.22	3.41	2.22
P ₂ O ₅		3.83	1.74	0.47
SiO ₂		56.85	40.82	20.42
TiO ₂		14.39	5.56	1.46

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Whilst the fuel could be considered slightly more aggressive than the most benign forestry residues, it has been successfully used in the Steven’s Croft boiler since 2008 where the final steam conditions are 136bar and 530°C. Fireside corrosion has been an ongoing issue in the furnace and has resulted in the progressive installation of Alloy 625 weld overlay to resist furnace wall corrosion. The primary superheaters are formed from low alloy steels and have been found to suffer corrosion-erosion damage, in which the flowing combustion gases remove the poorly protective corrosion scales. The secondary and tertiary superheaters are formed from HR3C austenitic stainless steels and have shown very low rates of corrosion, although it remains unknown if this would be the case at significantly greater final steam temperatures.

It is currently proposed that Doosan will undertake their planned plant scale fireside corrosion probe exposures within the Steven’s Croft boiler and, as such, the selection of this fuel for the pilot scale testing and for equivalent simulated laboratory scale testing, ensures the greatest continuity in testing between the partners making corrosion measurements.

2.3. Waste Industrial Wood

As shown above, waste industrial wood can contain significantly greater quantities of detrimental and generally undesirable ash forming elements which requires boilers firing such a fuel to operate with restricted steam conditions, typically of less than 100bar and 500°C, resulting in relatively low plant efficiency, even when employing some forms of fireside corrosion protection. The undesirable elements include Cl, alkali metals (Na, K) and heavy metals (Zn, Pb, etc.). The Blackburn Meadows bubbling fluidised bed fired power plant, owned and operated by E.ON, is located in central England and fires demolition wood. The fuel is known to be aggressive resulting in the plant operating with very modest final steam conditions of 81bar and 490°C. Despite these relatively low steam conditions the furnace and the final superheater has required protection from fireside corrosion using both refractory and Alloy 625 weld overlays. The hottest section of the final superheater is also exposed to relatively high flue gas temperatures close to the furnace exit with this combination deemed too aggressive for even Alloy 625 weld overlay to provide effective protection. Typical fuel analyses are shown in the tables below.

Table 5. Typical Fuel Analysis for the Demolition Wood Fuel.

		Units	Max	Mean	Min
As Received Analysis	Moisture	%	35.2	20.7	14.9
	Volatiles	%	66.9	61.8	48.8
	Fixed Carbon	%	16.1	14.6	11.6
	Ash	%	7.0	2.9	1.2
	Calorific Value (Higher Heating Value)	kJ / kg	16674	15413	12109
	Sulphur	%	0.16	0.06	0.03
	Chlorine	%	0.49	0.12	0.05
	Hydrogen	%	4.74	4.37	3.42
Net	Calorific Value (Lower Heating Value)	kJ / kg	15281	13968	10508
Dry Analysis	Ash	%	9.2	3.6	1.6
	Calorific Value	kJ / kg	19896	19434	18168
Dry Ash Free Analysis	Volatiles	%	82.0	80.9	80.3
	Calorific Value	kJ / kg	20429	20170	19945
	Hydrogen	%	5.80	5.72	5.65

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Table 6. Mean and Range of Monthly Composite Ash Analyses for the Demolition Wood Fuel.

Element	Units	Max	Mean	Min
Al	mg/Kg	1641	1158	449
Co	mg/Kg	3.02	2.245	1.48
Cr	mg/Kg	39.6	24.71	14.8
Cu	mg/Kg	98.1	43.16	22.71
K	mg/Kg	1126	981.8	752
Mn	mg/Kg	116	100.3	77.85
Na	mg/Kg	1388	889.5	644
Ni	mg/Kg	3.95	3.104	1.96
Pb	mg/Kg	279	209.1	100
Sn	mg/Kg	23.6	6.705	1.77
Tl	mg/Kg	<8	3.36	2.4
V	mg/Kg	6.59	3.025	1.02
Zn	mg/Kg	249	127.2	59.3
As (as hydride)	mg/Kg	23.8	13.35	5.43
Sb (as hydride)	mg/Kg	14.7	9.058	2.58
Cd	mg/Kg	1.04	0.561	0.4
Hg	mg/Kg	0.5	0.092	0.02
F	mg/Kg	24	14.47	9.02
Br	mg/Kg	<22	-	-
Al (metallic)	mg/Kg	309	128	72.3
Ash Oxide Matrix (Corrected for SO₃) (weight %)				
Al ₂ O ₃		10.12	6.96	4.26
BaO		1.17	0.74	0.13
CaO		29.59	24.18	16.50
Fe ₂ O ₃		5.67	4.65	3.75
K ₂ O		5.28	3.98	3.26
MgO		4.19	3.59	3.13
Mn ₃ O ₄		0.69	0.47	0.32
Na ₂ O		5.48	3.90	2.66
P ₂ O ₅		1.58	1.23	0.97
SiO ₂		49.01	39.62	32.36
TiO ₂		16.65	10.66	5.94

It is currently proposed that Uniper will undertake their planned plant scale fireside corrosion probe exposures within the Blackburn Meadows boiler and, as such, the selection of this fuel for the pilot scale testing and for equivalent simulated laboratory scale testing, ensures the greatest continuity in testing between the partners making corrosion measurements.

3. Summary and Gap Analysis

Work Package 1 “Foresight & Definition of Requirements” has 7 sub-tasks with Task 1.1 being the “Selection of Biomass Fuels”. This report covers the works conducted under Task 1.1 and is considered as the final deliverable under this task.

A survey has been conducted of the various biomass fuels and 3 generic types have been identified as being of sufficient commercial interest, i.e. sufficient quantities available for plant operation, and with combustion products that offer challenging environment in which to trial the candidate coatings. The 3 fuels identified for use within the BELENUS project are agricultural straw to be sourced from Spain; forestry residue to be sourced from Scotland and waste industrial wood to be sourced from England.

The agricultural straw usually contains high amounts of K and Cl, which reacts with Si and S leading to liquid or solid ash deposits and is considered to be a mid-range corrosive fuel. Cereal straw has been selected as it is used commercially in 3 reference plant namely Sangüesa (Navarra), operational since 2002, Briviesca (Burgos) and Miajadas (Cáceres), operational since September and November 2010, respectively. All 3 of these plant are reference installations with regards to biomass development for electricity generation in the south of Europe. These 3 plants process a total of 400.000 tons annually of cereal straw and other agricultural residues to generate enough electricity to supply 140.000 homes, without increasing CO₂ emissions.

The forestry residues fuel selected is that used commercially in the Steven’s Croft bubbling fluidised bed boiler, in southern Scotland, which usually has high metal and chlorine content but considered the more benign of the biomass fuels in terms of corrosion. The Steven’s Croft boiler fires forestry waste blended with a small proportion (<15%) of recycled wood fibre, the latter sourced primarily from recycled wooden furniture / cabinets, i.e. chipboard and Medium Density Fibreboard (MDF). The combination of recycled fibre and local forestry waste is sourced in a region called the lead hills, means that the fuel contains enhanced levels of the heavy metals Zn and Pb compared to many other forestry residues. This fuel mix has been used since 2008 where the final steam conditions are 136bar and 530°C.

The industrial waste wood selected is that used in the Blackburn Meadows bubbling fluidised bed fired power plant located in central England and contains high amount of Cl, alkali and heavy metals, leading to potential severe corrosion problems in boilers. The Blackburn Meadows plant fires demolition wood that is known to be aggressive and even though the plant operating conditions of 81bar and 490°C are considered to be conservative, the final superheater has required protection from fireside corrosion. Even so, in parts of the final superheater, close to the furnace exit, corrosion is deemed too aggressive for even Alloy 625 weld overlay to provide effective protection.

All 3 fuel sources have been analysed for combustion species and ash products so that in the laboratory screening tests environments similar to those found in the plant can be simulated. This data will be communicated to the partners and will satisfy the milestone M1.1. The 3 fuels identified in this deliverable will also be used for the pilot scale testing and circa 3 tonnes of each biomass is being sourced and will be transported to the pilot test facility at CIEMAT. With the issue of this report deliverable D1.1. will be considered complete.

4. Degree of Progress

With the issue of this report deliverable D1.1 is considered to be complete. Consequently Task 1.1 “Selection of Biomass Fuels” is completed.

5. Dissemination Level

Milestone M1.1 “Specific Biomass Fuels Selected” and deliverable D1.1 “Selection of Biomass Fuels” will be issued to all BELENUS partners via email and copies lodged on the BELENUS database. Deliverable D1.1 will also be uploaded to the EU portal by the project Co-ordinator.

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