Wood Biomass Pellet Characterization for Solid Fuel Production in Power Generation

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Abstract: - This study aims to compare fuel properties of wood pellet and torrefied wood pellet with coal. Some demerits of woody biomass as fuel include low energy density, high moisture content, easily susceptible to microbial degradation, supply is seasonally dependent, varies chemical and physical properties that has negative effect on the combustion efficiency and transportation. The efficiency of coal power generation on the other hand is around 30% to 40% and released more carbon as compared to biomass. There were five experiments conducted in this study to characterise the chemical and physical properties of coal, wood pellet and torrefied wood pellet namely moisture analysis, Thermo gravimetric Analyser (TGA), Bomb Calorimeter, Organic Elemental Analyser and Scanning Electron Microscope (SEM). The combination of torrefaction and palletisation is promising for upgrading woody biomass to produce to produce less greenhouse gases (GHG) emission like carbon dioxide (CO_2) sustainable and contain less sulphur oxides (SO_X) and nitrogen oxides (NO_X) compared to be used as solid fuel for power generation.

Key-Words: Torrefaction, wood pellet, coal, solid fuel, biomass, power generation

1 Introduction

Fossil fuels are primary fuel sources to generate energy in the world since 1900. At present, the energy demand has been increased rapidly together with the globalisation, modernisation, changing of lifestyle and population increased. Therefore, there are challenges with the depletion of fossil fuels and consequences of the increased emission of GHG particularly CO_2 from power generation. The renewable energies provide a better option for fossil fuel replacement for power generation due to more environmental friendly, carbon neutral and sustainable. Despite biomass, other renewable energy like wind and solar lacking in consistency of power generation to meet power demand. Biomass particularly torrefied wood pellet can be used to meet the power load requirements as similar to coal due to improved fuel characteristics similar to coal. However, there is challenge in feedstock availability of torrefied wood pellet in large power generation plant as the feedstock cost is higher than coal.

The similarity of biomass fuel characteristics with fossil fuels make it unique to be used for power, heat and fuel generation. The biomass is carbon sequester where the CO_2 generated from combustion can be reuse for plant growth during photosynthesis.

The main advantage of biomass as compared to coal is the availability to produce less CO_2, reduce emission of SO_X and NO_X. However, the technical and economic challenges of biomass is low bulk and energy density and low calorific value that cause the high feedstock cost. Besides, the high moisture content resulted in decrease plant efficiency, storage and handling problem.

There are few of pre-treatment techniques that have been develop based on biomass characteristics with aim to enhance the bulk and energy density of feedstock to make the storage, transportation, handling and thermal conversion more efficient and cost effective. Generally, the pre-treatment includes drying, pyrolysis, palletisation and briquetting and torrefaction.

The physical and chemical properties of coals and biomass varies; hence it is important to be able to determine the chemical composition as this often affect the combustion characteristics. Classification of coals ranks is often based on the determination of calorific value, the heat released by the fuel when it is completely burned at standard pressure (1 bar) and reference temperature (298 K). Obviously, the higher the calorific value, the greater the heat release. High quality coals, such as anthracites and bituminous coals, can be expected to have calorific values in the range 25 to 33 MJ/kg; low quality coals, such as lignite, and peat-based fuels have calorific values of under 20 MJ/kg. Therefore, this study focused on characterisation of wood pellet and torrefied wood with coal for upgrading as fuel in power plant.

2 Materials and Methods

2.1 Raw Materials

The coal sample was collected from Kellingley colliery located in Knottingley in West Yorkshire that produces approximately 50 kt/wk from the Beeston seam and supplied 95% of the coal to Drax power station in North Yorkshire by rail and give a product ash of about 16%. The wood pellets source was from virgin timber in United Kingdom (UK) forest and supplied by Logs2U, a part of CPL Distribution Ltd, the UK's largest coal and solid fuel supplier. The pellet has 6mm diameter and 40 mm maximum length in size. The manufacture claim that the ash content was less than less than 0.7%, moisture content of less than 10%, energy content calorific value of 4800 kWh/1000 kg and mechanical durability of more than 97.5%.

The torrefied wood pellets are supplied by New Biomass Holding LLC located in United States of America. The torrefied wood was claimed to be ground and extruded using a non-hazardous organic binder in a torrefaction reactor at 300 °C with low oxygen environment to remove moisture. The pellet has low energy volatiles, increased energy density to ease handling and transportation to coal plants. It is claim that the torrefied wood pellet sample has energy content between 20 to 23 GJ/MT [1].

2.2 Sample Preparation

All of the analysis were done in accordance with the procedure of American Society for Testing and Materials Standard Test Method for Chemical Analysis of Wood Charcoal [2] and Standard Test Methods for Analysis of Wood Fuels [3].

The samples were finely ground using Planetary Ball Mill PM100 using high centrifugal forces and very high pulverization energy to give short grinding times. The fine particles were separated using Analytical Sieve Shaker AS200 Basic to get fine particle size of less than or equal to 250 µm as accordance to according to ASTM D5865 (2013) and ASTM E1757 (2007) [4]. Then, the prepared raw materials were placed in plastic container and stored in a desiccator at room temperature until the analyses were carried out.

2.3 Moisture Analysis

Standard drying program in the Mettler Toledo Deluxe Halogen Moisture Analyser HR83 instruments is selected for moisture analysis where the samples is heated to set drying temperature and held constant at this temperature. The suitable drying temperature was set at 105 °C in accordance to ASTM D1762 (2013) Standard Test Method for Chemical Analysis of Wood Charcoal with drying time of 12 minutes. Moisture is determined by establishing the loss in weight of the sample when heated under rigidly controlled conditions of temperature, time and atmosphere, sample weight, and equipment specifications. For reliabilty of the result, the equipment was calibrated and analysis was repeated at least three (3) times [5].

2.4 Calorific Value

The determination of calorific value of coal and biomass samples in accordance with the ASTM D5865 Standard Test Method for Gross Calorific Value of Coal and Coke [6] and standard operating procedure Parr 6000 Calorimeter [7].

The bomb calorimeter model Parr 6200 was used in which the sample is burned in oxygen under standardised conditions. The fuel is placed in the central container (the bomb), which is surrounded by a water jacket. The fuel is ignited, and the energy liberated is transferred to the water. A thermometer measures the rise in temperature, from which the amount of heat released may be calculated. The calorific value can then be determined after corrections are made for the heat liberated by the ignition wire. The bomb calorimeter was assumed to be perfectly insulated where the heat released by coal is equal to heat gained by water. As the calorific value is reported as heat released per kilogram of dry fuel hence it is essential the moisture content is measures with appropriate correction made [7]. For reliability of the result, the analysis was repeated at least three (3) times

2.5 Proximate Analysis

In thermogravimetric analysis the mass of a sample in a controlled atmosphere is recorded repeatedly as a function of temperature or time, or both. Proximate analysis is conducted to determine moisture content, volatile matter, fixed carbon and ash content by mass [8]. Two types of gas involved during combustion, Nitrogen (N_2) and Oxygen (O_2). There were a few steps for TGA Analysis. Firstly, the Nitrogen gas was used at flow rate of 20 ml per minute. The powdered sample of 10mg to 20mg weight with size less than or equal to 250µm was use on the TGA analysis. Next the sample was hold at 40°C for 1 minute before heated from 40°C to 110°C at 65°C per min where the moisture loss occurs. Afterward, the sample was hold at 110°C for 3 min followed by heating from 110°C to 900°C at 100°C per min where the volatilization process or thermal decomposition of volatile gases such as Carbon Monoxide (CO), Carbon Dioxide (CO_2), Hydrogen (H_2) and water (H_2O) occurs. Later, the sample was hold at 900°C for 1 minute before switching to Oxygen gas with set flow rate of 40 ml per minute. Lastly, the sample was heated from 900°C to 950°C at 50°C per minute where fixed carbon loss occurs and only the ash remains at the end of the analysis [9]. For reliability of the result, the analysis was repeated at least three (3) times.

In this experiment, Perkin Elmer TGA 4000 model was used and upon completion of the TGA scan, the software Pyris was used to compute the weight percentage (wt. %) change for moisture, volatile matter and fixed carbon. The ash content was find from subtraction of one hundred for the wt. % changes for moisture, volatile matter, and fixed carbon.

2.6 Ultimate Analysis

Ultimate analysis by mass is given in terms of the chemical elements that make up the coal and biomass such as carbon, hydrogen, nitrogen and sulphur. Firstly, the 2.5-Bis (5-tert-butyl-benzoxazol-2-yl) thiophene (BBOT) standard reference material and samples with vanadium pentoxide (V_2O_5) catalyst were weighed in Tin capsules before placed inside the Thermo Scientific MAS 200R auto sampler. The V_2O_5 ensures complete conversion of inorganic sulphur in the sample to sulphur dioxide. The BBOT standard give the calibration reference of 72.53% carbon, 6.09% Hydrogen, 6.51% Nitrogen and 7.44% Sulphur. When the tin crucible with sample is dropped into the reactor, the oxygen environment triggers a strong exothermic reaction. Temperature rises to 1800°C, causing the sample to combust. The combustion products are conveyed across the reactor, where oxidation is completed. Nitrogen oxides and sulphur trioxide are reduced to elemental nitrogen and sulphur dioxide and oxygen excess is retained. The gas mixture containing N_2, CO_2, H_2O, and SO_2 flows into the chromatographic column, where separation takes place. Eluted gases are sent to the thermal conductivity conductor (TCD) where electrical signals processed by the Eager 300 software provide percentages of nitrogen, carbon, hydrogen, and sulphur contained in the sample [10].

Carbon (C), Hydrogen (H), Nitrogen (N) and Sulphur (S) are observed through organic elemental analyser FLASH 2000 CHNS with auto sampler MAS 200R from Thermo Scientific. The pre-packed CHNS reactor was used for organic elemental analysis. The basic elemental analysis is weighing, combustion, chromatography, and signal detection, analogue to digital conversion and calibration or sample composition calculation.

2.7 Microstructures

The function of scanning electron microscope (SEM) is by scanning images with a focused beam that produces electrons. The atoms that interact with the electrons produces signals that produces information on sample topography and composition. In this experiment, the JSM-6010LA SEM model observed the surface structure by secondary electrons, the specimen distribution of material backscattered electrons and the energy dispersive X-ray analyser (EDS) analyses elements in a specimen [11].

The microscope switch and software must be running and started the analysis by simply switched on the monitor. The samples must properly mount on suitable stubs with a coated metal to insulate sample. The sample was inserted properly at the stage wound down to 40 using right hand scale, change button and set specimen was selected. The vent chamber took about 1 minute. The sample was cleaned with nitrogen gas to make sure dry and dust free before putting into the microscope. The stub was slide onto the positioning pin. The desired sample was selected, and the experiment began after the pump the started. The software showed the image and the image was magnified and focused to get sharp image [11].

3 Results and Discussions

3.1 Characteristics of Coal, Wood Pellet and Torrefied Wood Pellet

The fuel characteristics of biomass is significant to determine the combustion characteristics in power plant. The calorific value, proximate and ultimate analysis of coal, wood pellet and torrefied wood pellet are presented in Table 1.

Samples		Wood Pellet	Torrefied Wood Pellet	Coal
Moisture Content (wt. %)		7.060	6.760	2.388
CV (MJ/kg)		18.78	20.68	32.00
Proximate Analysis (wt.%)	Moisture	4.634	3.629	1.233
	VM	74.30	65.20	33.55
	FC	20.80	28.85	62.62
	Ash	0.261	2.321	2.593
Ultimate Analysis (wt. %)	C	49.06	59.45	76.33
	H	6.311	5.993	4.801
	N	2.079	0.4078	1.446
	S	0.000	0.1656	1.825

Table 1: Chemical and Physical Properties of Wood Pellet, Torrefied Wood Pellet and coal

From the result, there were difference in value of moisture content analysed using moisture analyser and TGA. The standard deviation errors were smaller in moisture analyser hence, the result was more reliable and accurate. This was due to the determination of moisture content taking into consideration of atmospheric pressure and temperature as compared to loss of moisture weight from TGA. In comparison with wood pellet, it can be seen that the moisture content and volatile matter of torrefied wood decreased due to devolatilization of wood during torrefaction. This result shows that torrefaction process reduce the moisture content as high moisture content will reduce the combustion efficiency and incurred in high drying cost.

In addition, torrefaction resulted in higher carbon content, calorific value, ash content and sulphur. The increasing calorific value for torrefied wood pellet is mainly related to the increase of carbon content. The torrefied wood pellet has a heating value which almost equals to a low-grade sub-bituminous coal (approximately 20 MJ/kg) [12]. From the result, the ash in coal is the highest at 2.593% followed by torrefied wood pellet and wood pellet at 2.321% and 0.2611% respectively. As coal and torrefied wood pellet is more brittle in structure the ash content is higher than fibrous wood pellet. On the other hand, the sulphur content in torrefied wood pellet is 0.1656% and no sulphur detected in wood pellet. The presence of sulphur in torrefied wood pellet most probably due to addition of organic binder during palletisation and torrefaction process.

Additionally, the hydrogen and nitrogen content of torrefied wood decreased resulting in decreased H/C ratio. Nevertheless, the woody biomass has greater volatile compound than sub-bituminous coal. The fuel ratio or ratio of fixed carbon content to volatile matter is 1/10 of coal.

Nonetheless, the moisture content and ash content for Kellingley coal was 1.233% and 2.593% correspondingly. The volatile matter, fixed carbon content, calorific values was 33.55%, 62.62% and 32.00 MJ/kg respectively. Hence, from the ASTM D388 (2012) to classify coals from the calorific value, in increasing coalition order Killingley coal was classified Bituminous High Volatile B. A high rank coal composed mainly of fixed carbon with little volatile content and ash, no or less moisture and high calorific value. Hence, the highest coal rank is more carbon neutral, high energy density, more brittle, hydrophobic in nature, low sulphur and ash than wood pellet.

3.2 TGA Curves

The thermo gravimetric analysis combustion profiles of coal, wood pellet and torrefied wood pellet are shown in TGA curves as in Figure 1, Figure 2 and Figure 3 respectively. The TGA curves represents the loss of weight of the samples at different temperature region where the weight loss of the biomass increased with increasing reaction temperature. At drying stage for the temperature below 200°C there is slight decay of the coal and biomass weight due light volatilization. Normally, the weight loss of the samples is less than 10%. After the temperature increased from 200°C to 500°C, a significant change in weight loss is observed due to thermal decomposition of hemicellulose, cellulose and lignin. There is no significant weight loss occurs when temperature is higher than 500°C mainly because of thermal decomposition of components.

From TGA curve of wood pellet and torrefied wood pellet in Figure 2 and Figure 3 respectively, it can be seen that the curve went slightly towards negative axis towards the end of analysis indicates the negative ash formation. As the TGA procedures for all samples are similar, the error occurs for biomass instead of coal due to the method for combustion of woody biomass should be adjusted at smaller scanning rate of nitrogen and oxygen gas with longer time to complete the TGA analysis as compared to coal.

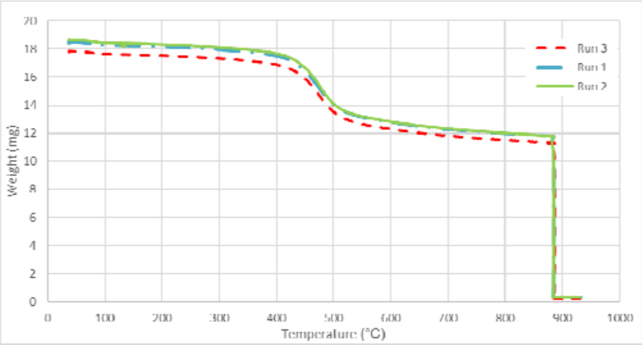

Figure 1: TGA Graphs of Kellingley Coals

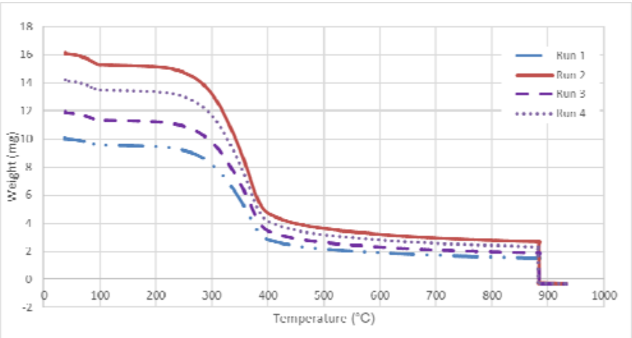

Figure 2: TGA Graphs of Wood Pellets

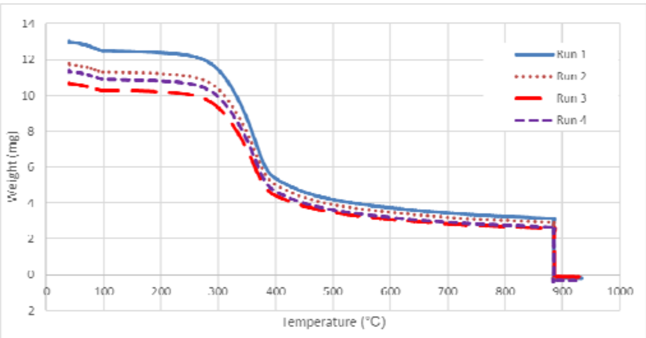

Figure 3: TGA Graphs Torrefied Wood Pellets

3.3 Microstructures

Woody biomass is composed of cellulose, hemicellulose and lignin. Drying wood for palletisation at temperature below 250°C softens lignin, devolatilised and carbonised hemicellulose. In contrast, during torrefaction drying at temperature above 250°C decomposed hemicellulose into volatiles and char. From the cross section of SEM photo of coal, wood pellet and torrefied wood pellets as in Figure 4, Figure 5 and Figure 6, it can be seen clearly the micro fibrils structure of wood pellet that contributes to hydrophilic in structure that easily susceptible to biological degradation. Torrefied wood pellet and coal is more brittle in structure and higher grind ability than fibrous wood. Hence more hydrophobic and stable in storage while wood pellets will deteriorate to gets mouldy. Under a higher temperature, wood pellet becomes more porous as all the cellulose, hemicelluloses and extractives will be reacted. The porous structure might absorb some inorganics, which might explain the increase in the ash content of torrefied wood pellet.

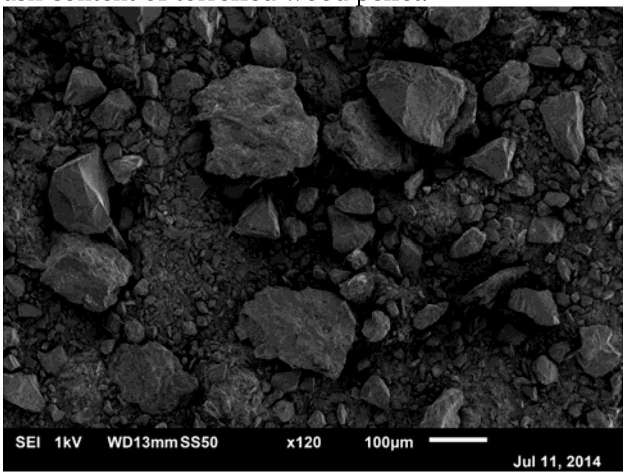

Figure 4: Microstructure of Coal

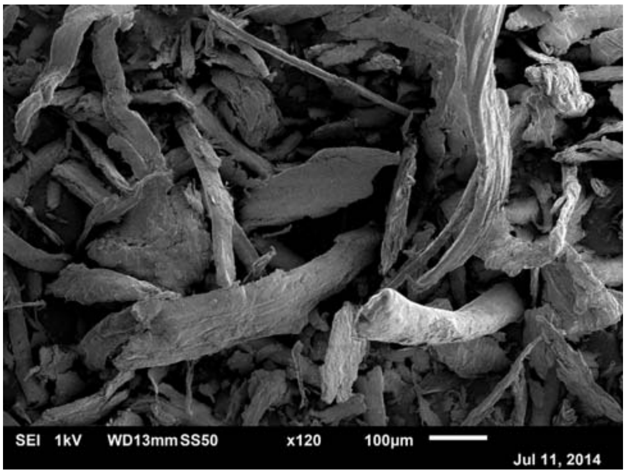

Figure 5: Microstructure of Wood Pellet

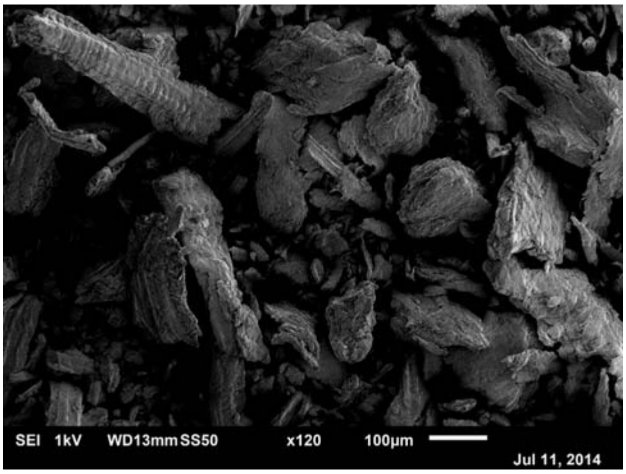

Figure 6: Microstructure of Torrefied Wood Pellet

3.4 Effect of Torrefaction on Fuel Properties

Torrefaction of wood pellet improved the fuel properties of the biomass as compared to wood pellet. The distinct improvement was seen on increased of calorific value and carbon content and decreased on moisture content, volatile matter, hydrogen and nitrogen content. However, the ash content and sulphur contents were increased in torrefied wood pellet. The presence of sulphur most probably due to addition of organic binder during torrefaction process by the manufacturer.

In general, torrefaction process of woody biomass that contains mainly cellulose, hemicellulose and lignin undergo thermal decomposition with the increasing temperature and leaves the char solid residue. Torrefaction process increases the energy density of biomass close to coal in addition to improve the storability and grind ability of biomass. The significant improve in feedstock properties will improve plant reliability, combustion efficiency, reduce collection and transportation cost, minimize fouling and slagging. Therefore, high rate co-firing of torrefied wood pellets with can be achieved.

Conversely, the current market price for torrefied wood pellet feedstock is more expensive than wood pellet and coal. Although the use of torrefied wood into existing coal power plants will substantially increase the fuel cost, the energy density of torrefied wood pellets is higher than wood pellet. Therefore, it is more economical to ship high energy per cubic meter. Additionally, the moisture content of torrefied wood pellets is lower than wood pellets at making them and more stable in handling and storage. In addition, torrified wood pellets is brittle in structure and higher grind ability than fibrous wood. Details economic analysis of implementation of torrefied wood in co-firing power plant should be discussed further.

On the other hand, there is also issue on the difference in quality of recycling of the ash generated compared to coal amongst the manufacturer with the use of wood pellet and other type of biomass. The sulphur and ash content of torrified wood pellets is lower than coal.

3.5 Plant Design Outline for Wood Co-Firing with Coal

The direct biomass co-firing with coal will improve the efficiency of overall plant performance. The energy efficiency of biomass co-firing will be increase with the implementation of combined heat and power (CHP). Direct co-firing in existing coal power plant requires less capital investment than dedicated biomass power plant.

The power generation plant energy conversion takes place in two (2) stages:

1. The first energy conversion efficiency is from the boiler performance during combustion. The basis normal assumption for well optimized power plant is assumed to be 88% efficiency on high heating value (HHV).
2. The second energy conversion takes place in the steam cycle efficiency. It is assumed that the co-firing coal-biomass power plant adopted modern Rankine cycle that have efficiencies varies from 35% to 44% [13]. In this report the assume efficiency value is 44% for our case.

Therefore, the overall conversion efficiency is (44% x 88%) 38.72 %.

For a given power output of 100 MW, the actual power from coal and biomass combustion needs to be determined considering the efficiency of the plant. The plant efficiency is assumed to be 38.72% as the torrefied wood pellet biomass fuel is used with coal. Therefore, the resulting required power to produce 100 MW of electricity is 258 MW (100/0.3872) or the input power is 258 MW to produce 100 MW of electricity. 1 watt of power is equivalent to 1 Joule
per second.

Table 2: Given and Assumption Data for Power Plant Design

	Coal	Torrefied Wood Pellet
Output Power Capacity	100MW	
Fuel	1.825% Sulphur, 1.446% Nitrogen	0.1656% Sulphur, 0.4078% Nitrogen
Heating Value (kJ/kg)	32,000	20,680
Plant Overall efficiency	38.72%	
Co-firing ratio	80%	20%

Next the energy per mass from coal and biomass needs to be considered. From Table 2 the calorific value of coal and torrefied wood pellet is 32 MJ/kg and 20.68 MJ/kg respectively. Hence, the mass of coal burnt per second is 258,000,000 J/s divided by 32,000,000 J/kg gives a mass of 8.06 kg/s of coal that needs to be burnt. Multiplying this figure 86400 (the number of seconds in a 24-hour period), 696,600 kg of coal burnt per day, or 696.6 tons per day. Therefore, 80% of coal is equal to 557,280 kg of coal burnt per day or 557.28 tons per day.

On the other hand, the mass torrefied wood pellet burnt per second is 258,000,000 J/s divided by 20,680,000 J/kg gives a mass of 12.48 kg/s of torrefied wood pellet that needs to be burnt. Multiplying this figure 86400 (the number of seconds in a 24-hour period) 1,007,911 kg of torrefied wood pellet burnt per day, or 1077.9 tons per day. Therefore, 20% of torrefied wood pellet is equal to 201,582 kg of coal burnt per day or 215.58 tons per day.

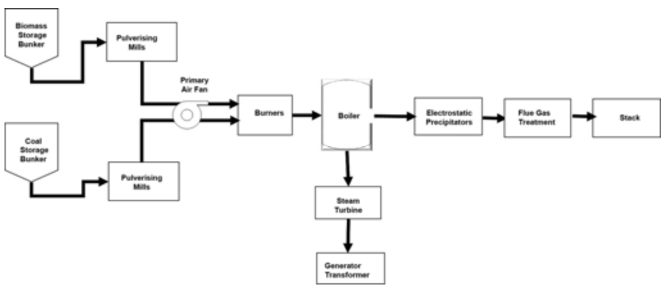

Figure 7: Direct Co-Firing Biomass-Coal Power Plant Outline

3.5.1 Economic Analysis

Economies of scale for biomass co-firing plants related with investment, operation, maintenance and fuel cost. The direct co-firing plant provides the cheapest and simplest options of low investment costs because it utilises the pre-existing boiler and other equipment in coal fired plant. The investment cost is depending on the plant capacity, service, type of biomass fuel, and existing boiler quality. The torrefied wood pellet and coal will be pre-milled before feeding into the same boiler. The estimated cost of retrofitting torrefied biomass in coal power plant is around £200/kW based on 2012 market condition [13]. In this project, the torrefied wood pellet will be co-fired with coal at coexisting power generation plant with output capacity of 100MW. Nonetheless, torrefaction plants would significantly incurred high capital costs and requires large feedstock availability to compensate for the investment but are expected to have lower operation costs than palletisation plants.

Co-firing of torrefied wood pellet with coal will increase the fuel handling costs but it will reduce the flue gas treatment and ash disposal cost as the sulphur, nitrogen and ash content are small as compared to conventional coal treatment plant. Therefore, the operation and maintenance cost almost similar to conventional coal fired plant within the range of £3.0/MWh to £6.03/MWh [13]. Moreover, the normal average O&M costs is approximately 2.5% to 3.5% of capital costs and the cost increase with the increase of quality torrefied wood pellet used and higher substitution ratio with coal. Torrefied wood pellet has low ash content than coal with properties almost similar to coal that could significantly contribute to fouling and corrosion problem boilers.

The torrefied wood pellet fuel cost consist of the cost of the feedstock that depends on the biomass origin and cost of transportation, preparation and handling. As torrefied wood pellets are imported from United States, the transportation costs depend on the energy density, calorific value of the fuel. Hence, torrified wood pellet increase the calorific value per volume of biomass fuel as compared to wood pellet. Besides, the torrefied wood pellet produce a more uniform size, hydrophobic and brittle that make the transportation, storage and handling easier. In addition, the torrefied wood pellet can be shipped in large amount as compared to wood pellet due to higher energy density and hydrophobicity, hence reduce the logistic cost.

3.5.2 Environmental Impact

Torrefied wood pellet has potential in reducing GHG emission due to many reasons. Firstly, woody biomass is a carbon neutral fuel as the CO_2 releases to the atmosphere during combustion will be used during photosynthesis. Therefore, substitution of coal with biomass release less net GHG emission than conventional coal power plant. Replacement of 1% to 10% biomass per year with coal could significantly reduce 45 to 450 million tonnes of CO_2 emissions in 2035 [13]. Therefore, substitution rate of more 10% biomass would have potential in negative GHG emissions. However, the CO_2 net reduction should consider the carbon released during the supply chain during shipping, handling and construction of co-fired plant.

Despite GHG emissions, co-firing coal with torrefied wood pellet reduces the emission of SO_x, NO_X and other harmful pollutants. The sweater flue gas desulphurisation provides the cheapest option in removal of gaseous pollutants due to low operating cost. Nevertheless, there is a concern on ultrafine particles or known as PM_{10} released from ash to cause health related problems with lungs such as respiratory problems and lung cancer. Hence, it is significant to install electrostatic precipitators or other gas cleaning equipment to filter and trap fine particles.

4 Conclusion

The fuel qualities of the product were improved after torrefaction; such as a higher carbon content, low H/C ratios, moisture content, volatile matter, hydrogen and nitrogen content as compared to wood pellet and coal. The calorific value of the torrefied wood pellet is equal to low-grade sub-bituminous coal.

In general, torrefaction improve the fuel properties of wood pellet similar to coal. The torrefied wood pellet is more economic in terms of fuel transportation, storage and handling cost due to high energy content, high bulk density and hydrophobic as compared to wood pellet. However, there is economic challenges for high rate co-firing substation of torrefied wood pellets. On the other hand, there are significant advantages in reduction of greenhouse gases (GHG) emission particularly Carbon Dioxide (CO_2), oxide of Sulphur (SO_x) and oxide of Nitrogen (NO_x) with the increasing co-firing ratio of torrefied wood pellet with coal.

Apart of above mentioned common aspects, the future work of this study can be further investigated on comprehensive evaluation of fuel properties such as ash elemental analysis and ash fusion test for evaluation of slagging and fouling tendencies for application of co-firing with coal. In addition, the pellet properties of wood pellet and torrefied wood pellet such as grindability, mechanical strength, hydrophobicity should be measured in comparison with coal. Besides, the feasibility study should be conducted for large scale co-firing power plant with capability to 100% fuel switching from coal to biomass it is beneficial to install torrefaction unit at the plant to benefit from logistic and shipping cost.

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