Proc. Pakistan Acad. Sci. 47(4):265-287.2010

A REVIEW ON BIOMASS–COAL CO-COMBUSTION: CURRENT STATE OF KNOWLEDGE

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Received April 2010, accepted September 2010

Abstract: The concept of "Energy from biomass" gained attention in the last decade in the context of clean electricity generation. It is still a developing field because of the unavailability of standard engineering practices in this area. The variations in the chemical composition and physical properties of biomasses have made this task lengthier. There are several parametric studies available in the literature on the co-firing of biomass with coal. The information on agricultural residue co-firing in conjunction with air and fuel staging is scarce. The idea of energy crops for co-combustion to get green energy needs review due to present food shortage crises in the world. Therefore, there is utmost need to explore the energy potential and environmental benefits associated with the agricultural wastes-coal co-firing. The present paper presents a review of the previous work and suggests a strategy for Pakistan to solve energy crises by utilizing its indigenous resources of coal and agricultural waste .

Keywords: Energy, biomass, renewable, climate change, bagasse

1. Inroduction

The role of renewables is continuously increasing due to climate change and energy security threats. By April 2009, 78 countries had signed the statute of the International Renewable Energy Agency (IRENA). Members include most countries of the European Union and many developing countries, from Africa to Asia-Pacific to Latin America, including Argentina, Chile, Ghana, India, Pakistan, Morocco, the Philippines, Senegal, South Korea, and Tunisi. By early 2009, 73 countries have renewable energy policy targets [1]. EU-25/EU-27 has a binding target of a 20% share of renewables in the energy consumption by 2020 [2]. Despite increasing share of renewables in energy generation schemes, new technologies are not yet competitive to combat climate change [3]. Probably the fastest and easiest way to replace large amounts of fossil fuel based electricity by sustainable electricity is to replace the combusted fossil fuels by biomass [4]. In this scenario, co-firing biomass residues with coal in traditional coal-fired boilers for electricity production represents the most cost effective and efficient renewable energy and climate change technology [4]. Co-combustion of biomass with coal for power generation is continuously increasing. During the last 10 years, a lot of progress has been made in the utilization of biomass in coal-fired power stations. Biomass power generation (and cogeneration) continued to increase at both large and small scales, with an estimated 2 GW of power capacity added in 2008, bringing existing biomass power capacity to about 52 GW [1]. Biomass power generation continued to grow in several European Union (EU) countries during 2007/2008, including Finland, France, Germany, Italy, Poland, Sweden, and the United Kingdom. China continued to increase power generation from industrial-scale biogas (i.e., at livestock farms) and from agricultural residues, mainly straw [1]. The sugar industries in many developing countries continued to bring new bagasse power plants online, including leaders Brazil and the Philippines, and others such as Argentina, Columbia, India, Mexico, Nicaragua, Thailand, and Uruguay [1]. Currently, over 234 units have the experience of co-firing biomass. A country wise distribution of these power

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Table. 1 Power plants with experience in co-firing combinations of biomass and fossil fuels.

Country	BFB	CFB	CFB,BFB	Grate	PF	Unknown	Total
Australia					8		8
Austria		3		1	1		5
Belgium					1		1
Canada					7		7
Denmark		1		4	7		12
Finland	42	13	6	4	10	6	81
Germany				1	4	22	27
Indonesia	2						2
Italy					6	1	7
Netherland					6		6
Norway		1					1
Spain		1				1	2
Sweeden	3	7		2	3		15
Taiwan		1					1
Thailand		1					1
UK		2			16		18
USA	1	5		5	29		40
Total	**48**	**35**	**6**	**17**	**98**		**234**

Source: [4]

plants is presented in Table 1. Recent studies in Europe and the United States revealed that burning biomass with coal has a positive impact both on environment and the economics of the power generation. The emissions like NO_x and SO_2 were reduced in most co-firing tests depending upon the biomass used. The CO_2 net production was also lower because biomass is considered CO_2-neutral.

2. A Review of Previous Work

2.1 Co-firing

Van den Broek *et al.* [5] presented overview of the biomass combustion in boiler technologies and quoted the efficiency of 37% for a 4.5% biomass co-fired pulverised coal boiler.

Pedersen *et al.* [6] carried out full-scale measurements on a 250 MW, pulverized coal fired unit using 10-20% straw (thermal basis). With an increased fraction of straw in the fuel, a net decrease in NO, and SO_2 emissions was measured. The SO_2 emission decreased partly due to the lower sulfur content of the fuel per MJ, but also due to higher sulfur retention in the ash. The NO emission decreased solely due to lower conversion of fuel-N. An increased fraction of straw in the fuel blend resulted in a higher potassium content, but no significant increase in slagging or fouling was observed. Only small amounts of deposit at the lower part of the radiant super heater and little slagging at the furnace walls were observed as a result of co-firing straw and coal.

Boylan [7] reported the tests conducted in June 1992 at Georgia Power Company's plant Hammond Unit I to evaluate the impact of co-firing wood waste with pulverized coal on plant performance. Hammond 1 is a 100 MW

Babcock and Wilcox (B & W) unit fuelled by pulverized coal. Over a three day period, 11 full load performance tests were conducted, five with coal and six with wood/coal mixture. A total of 125 tonnes (as received, 19% moisture) was burned, the wood waste a mixture of sawdust and ground tree trimming waste. Wood percentage in the fuel ranged between 9.7 and 13.5%, with an average for the co-fire tests of 11.5% (all percentages by weight). At medium and high O_2 levels, boiler efficiency with wood co-firing was within 0.2-0.4% of boiler efficiency with coal alone.

Hunt *et al*. [8] presented the results for Unit 2 and Unit 3. Unit 2 is a 138 MWe (gross) wall-fired pulverized coal boiler equipped with ball and race mills, table feeders, and low-NO_x burners. Unit 3 is a 190 MWe (gross) tangentially-fired pulverized coal boiler equipped with bowl mills, paddle feeders, and low-NO_x burners. Firstly, the project tested the use of blended bio fuels in boilers equipped with low NO_x burners. Additionally, three types of bio fuels were tested: (1) mill waste sawdust, (2) utility right-of-way trimmings, and (3) harvested hybrid poplar. For both units, the 3 weight percent bio fuel blends behaved like wet coal. Three percent wood co-firing produced significant negative impacts in the pulverizing systems, leading to significant boiler capacity reductions in both a wall-fired PC boiler and a tangentially fired PC boiler. They recommended separate injection of wood to avoid the negative impacts experienced during the testing.

Ekmann *et al.* [9] discussed the status of co-firing coal with biomass and other wastes in the light of International Survey of co-firing coal with biomass. They reported co-firing of waste tyres, municipal solid waste, and wood waste up to 10% in units designed for pulverised coal.

Bain *et al.* [10] suggested biomass fired power generation for village power applications in the 10-250 kW scale, for larger scale municipal electricity and heating applications such as hog-fuel boilers, in agricultural applications such as electricity and steam generation in sugar cane industry and for utility scale electricity generation in the 100 MWe scale. They described biomass based systems only non hydro renewable source of electricity. They reported number of companies engaged in co-firing operations in USA like Northern States Power (NSP), Georgia Power, Santee Cooper, Savannah Electric, and Tennessee Valley Authority (TVA). They reported that NSP routinely co-fires 200,000-300,000 t/year of biomass. They predicted that 5-8% of the wood can be co-fired with coal

Robinson *et al.* [11] investigated blends of coal red oak wood chips, wheat straw and switch grass using 30 kW multifuel down fired combuster. They concluded that blending coal with biomass fuel that has low fuel-bound nitrogen can result in reduced NO_x emissions but there is no evidence of fundamental synergistic interaction between the coal and biomass that results in significantly reduced NO_x emissions but the potential of high volatile yields and moisture contents can be exploited to reduce NO_x.Their experimental results demonstrated reduction in pollutant production, decreased ash deposition and decreased effective CO_2. They linked their findings with judicious selection of fuels and operating conditions.

In year 2000, Tillman [12] wrote an editorial in a journal titled “Biomass and Bio energy” in which he stated “Every tonne of biomass co-fired directly reduces fossil CO_2 emissions by over 1 tonne. Co-firing is in its infancy today. If we can not make co-firing work as commercial technology for electricity generations, it is doubtful that we can make the more far-reaching technologies a commercial reality". He strongly advocated co-firing as low cost, low risk, renewable strategy.

Tillman [13] reviewed the co-firing experience of various organisations in USA like Electric Power Research Institute (EPRI), TVA, GPU Genco, Northern Indiana Public Service Company (NIPSCO), Central and South West Utilities (C&SW), Southern Company, Madison Gas & Electric (MG&E), New York State Electric and Gas (NYSEG). These companies blended 5-20% of the wood waste with coal. He advocated for co-firing due to environmental benefits of reduced NO_x, SO_2, and CO_2 for electricity generation despite the reduction in boiler efficiency reported at various stations.

Sami et al. [14] reviewed the state of knowledge on burning of pulverised coal and biomass. In their review, they anticipated that blending biomass with higher quality coal would reduce flame stability problems as well as corrosion effects. They suggested that synergetic effects of blending coal and biomass may also lead to reduction in other emissions like NO_x, SO_x and CO_2. Authors quoted name of the 32 full scale utility boilers where co-firing tests performed using waste wood, sander dust, saw dust, plastic waste, willow, grass crop and forest debris as biomasses Most of the utilities used wood. They concluded that fundamental combustion studies must be performed, particularly for pre-mixed coal and biomass fuel blends, in order to determine combustion behaviour characteristics in controlled laboratory settings. They described coal biomass combustion a promising technology for electric utility despite of all the issues and concerns.

Campbell *et al.* [15] investigated the coal char and biomass char reactivities to oxygen using thermogravimetric analyzer. Their findings indicated that the almond shell chars are more than 1000 times more reactive than the chars of the bituminous coal examined. Demirbas [35] described biomass as CO_2 neutral fuel as it absorbs carbon dioxide during growth and emits it during combustion. Therefore, biomass helps the atmospheric carbon dioxide recycling and does not contribute to the green house effect. He stated that co-firing biomass with coal has the capability to reduce both NO_x and SO_x levels from the existing pulverised coal fired power plants. Additionally, biomass as combustion feed stock is more reactive as a fuel and resulting char. Moreover, despite the difference in heating values of coal and biomass, dry biomass and dry coal have similar adiabatic flame temperatures. He presented physical properties and ultimate analysis of red wood oak and wheat straw.

Surmen and Demirbas [16] investigated combustion characteristics of hazelnut shell, lignite and their blends using TGA. While discussing the environmental and economic benefits of the co-firing they expressed that the concept of co-firing with biomass to alleviate environmental problems can have its inception in international concerns over perceived global warming, regional acid rain precipitation and local difficulties associated with waste disposal.

Backreedy *et al.* [17] found that biomass char are more reactive than coal char due to activation of the bonds by –O– groups present in the structure.

Savolainen [18] reported the results of co-firing tests with sawdust and coal that were carried out at FORTUM's Naantali-3 CHP power plant (315 MW fuel). The Naantali-3 plant is a tangentially-fired pulverised-coal unit with a Sulzer once-through boiler that produces 79 MWelectricity, 124 MW district heat and 70

MW steam. Naantali-3 is equipped with roller coal mills (Loesche), modern low-NO_x burners (IVO RI-JET), over-fire air (OFA), electrostatic precipitator (ESP) and flue-gas desulphurization plant (FGD). Coal and sawdust were blended in the coal yard, and the mixture fed into the boiler through coal mills. Tests were carried out for three months during the April 1999 to April 2000 period with pine sawdust (50-65% moisture, as received). During the tests, sawdust proportions of 2.5–8% (from the fuel input) were examined. The co-firing tests were successful in many ways, but the behaviour of the coal mills caused some problems, and therefore the simultaneous feed will not be the solution in a long-term use. A separate bio fuel grinding system and bio- or bio-coal-burner were developed. By using this system, it is possible to utilize many kinds of bio fuels in PC-boilers as well as increase the share of bio fuels, compared to the simultaneous feed of bio fuel and coal.

Demirbas [19] discussed combustion characteristics of different biomass fuels like hazelnut shell, wheat straw, olive husk, spruce wood, walnut shell etc. He discussed the physical and chemical properties, proximate and ultimate analysis of the biomasses. He found structural, proximate and ultimate analysis results of biomasses considerably different. While concluding, he presented his opinion that co-combustion of biomass with coal in comparison with single coal helps reduce the total emissions per unit energy produced.

Ye *et al.* [20] performed an experimental investigation on the co-combustion of propane with pulverized coal, pine shells, and textile wastes. Experiments were performed in a large-scale laboratory furnace fired by an industrial-type swirl burner. The co-firing of propane with pine shells and textile wastes yielded particle burnout values much higher than that of the propane-coal flame despite the similarities of the three flames revealed by the in-flame data. They attributed this to the higher volatile matter content of the pine shells and textile wastes, in spite of their much larger particle sizes, compared with that of coal.

Baxter [21] highlighted the benefits of biomass and coal co-combustion as low risk, low cost, sustainable, renewable energy option that promises reduction in net CO_2, SO_x and NO_x emissions along with several societal benefits. He also mentioned challenges associated like supply, handling, storage, potential increase in corrosion, fly ash utilisation etc. He concluded that issues associated biomass combustion are manageable but require careful consideration of fuels, boiler operating conditions and boiler design.

Demirbas [22] while describing biomass coal co-firing in boilers revealed that biomass like spruce wood, beech wood, hazelnut shell, wheat straw and tea waste have higher volatile matter yield than coals: the biomass fuels have VM/FC ratio typically>4:1 as compared to VM/FC of coal of virtually always<1:0. He found that greater is the VM/FC ratio greater is the reduction in NO_x. A laboratory scale bubbling fluidised bed combustor was used for experiments. He endorsed the co-combustion of biomass with coal as an effective method to reduce NO_x, SO_2 and ash volume for coal fired power plants.

Grammelis *et al.* [23] investigated the alterations of ash quality and utilisation aspects when coal was co-fired. Co-combustion tests were performed in lab and semi-industrial scale facilities, using several coal–biomass blends. The biomasses used with coal were forest residues, olive kernels, pine wood and oak wood. They found that biomass exploitation as secondary fuel in co-combustion processes is technically and economically feasible up to 20% w/w and the produced ash could be further utilised without any major treatment. At enhanced percentages of biomass fuels mixed with coal, the utilisation of co-combustion residues is restricted by the unburnt carbon content and not the free lime, which is reduced. Kruczek *et al.* [24] performed experiments in the 20 kW isothermal flow reactor (IFR) to determine the effect of combustion temperature and of the presence of biomass on NO_x and SO_2 emission and the burnout. The reactor was supplied with hard coal and brown coal, containing a fixed share of biomass (10, 20 and 50% of mallow Petemi or sawdust, on mass basis). The effect of biomass addition on the devolatilization and combustion rate was higher for lignite than for hard coal. The amount of NO_x formed and SO_2 emission was found to increase with an increase in temperature. The effect of the combustion temperature is more pronounced over a wider range of excess air and numbers for coarser particles (d = 0.2–0.5 mm) than or fine ones, d<0.2 mm. The amount of NO_x emission depends on the combustion mode, the occurrence of oxygen-deficient combustion zones and the volatile matter content of the fuel. The mode of combustion was found to have no significant effect on the total SO_2 emission, which depends mainly on the sulfur content in the fuel, the temperature, the residence time and the heating rate. An increase in the biomass fraction in the fuel results in a decrease in the NO_x and SO_2 emission, but to different degrees, depending on particle size and type of coal and biomass. A reduction in the NO_x emission for coal of particle size below 0.2mm burned with biomass was noticeable for higher air excess numbers. The decrease in the NO_x emission with biomass addition increased with the amount of addition (of sawdust). The degree of burnout increased with increasing proportion of biomass (sawdust) and the effect is stronger for lignite than for hard coal.

Kazagic and Smajevic [25] investigated ash and emissions behavior during combustion of Bosnian coal and biomass. For co-firing test trials, there was no significant difference recorded in the ash deposit characteristics of the coal–biomass ash samples (Kakanj brown coal–spruce sawdust) against the single coal ash samples (Kakanj brown coal) at temperature up to 1250°C. Above this temperature, fouling is accentuated for the coal–biomass blends. For both of the coal–biomass blends tested, there was a reduction of NO_x of 50% as the process temperature reduced from 1400 to 960 °C (down from 1600 to 800 mg/m^3_n normalized to 6% O_2 dry, $\lambda=1.2$). On the other hand, less SO_2 was measured for coal–biomass combustion compared to brown coal alone; at 1140 °C, there was 15% less SO_2 for the 7%(by wt) blend of spruce-coal than the Kakanj coal alone, while it was 28% less for the 20% blend of spruce –coal.

Narayanan and Natarajan [26] investigated co- firing of bituminous and lignite coal with bagasse, wood chips, sugar cane trash and coconut shell in a 18.68 MW travelling grate boiler. They reported 50% reduction in SO_2 emissions and 45% reduction in NO_x emissions against coal: wood combination of 40:60.

Kwong *et al.* [27] investigated co-combustion performance of coal with rice husks and bamboo in a laboratory scale combustion facility. The aim was to determine the effect of biomass blending ratio, relative moisture content and particle size of biomasses on the gaseous emissions. Gaseous pollutant emissions including CO, CO_2, NO_x, SO_2 were reduced. A range of 10-30% biomass blending ratio (BBR) on thermal basis was found to be the minimum pollutant factor. With an increase in moisture content in biomass, decrease in combustion temperature, SO_2, NO_x, CO_2 emissions were observed, while an increase in CO emissions was found. No effect of biomass particle size on fuel burning rate and pollutant emissions were found.

Damstedt *et al.* [28] investigated the effect of biomass co-firing on emissions and flame structure. They described that the NO emission was seen to decrease as the straw primary air flow rate increased because of increased numbers of fuel-rich eddies providing more reducing zone, where the fuel nitrogen from the large particles was released. They found that that the fuel-rich eddies served as reburning and/or advanced reburning centers, reducing the effluent NO emission further.

Leckner [29] reviewed co-combustion technology and mentioned several options: co-combustion with coal in pulverised or fluidised bed boilers, combustion on added grates inserted in pulverised coal boilers, combustors for added fuel coupled in parallel to the steam circuit of a power plant, external gas producers delivering its gas tore place an oil, gas or pulverised fuel burner. Furthermore, biomass can be used for reburning in order to reduce NO emissions or for after burning to reduce N_2O emissions in fluidised bed boilers. Combination of fuels can give rise to positive or negative synergy effects, of which the best known are the interactions between S, Cl, K, Al, and Si that may give rise to or prevent deposits on tubes or on catalyst surfaces, or that may have an influence on the formation of dioxins. With better knowledge of these effects the positive ones can be utilised and the negative ones can be avoided.

Lu *et al*. [30] reported little effect of the amount of biomass addition on flame stability provided that the addition is less than 20%.

Haykiri-Acma and Yaman [31] investigated effect of co-combustion of Turkish Elbistan lignite and woody shells of hazelnut on burn out using TGA. They found that biomass addition has synergistic effect on the burn out. They added hazelnut shells up to 20 wt%.

Molcan *et al.* [32] performed experimental investigations into the co-firing of pulverised coal directly co-milled with 5–20% biomass on a 3 MWth Combustion Test Facility. The results suggest that, due to the varying physical and chemical properties of the biomass fuels, the biomass additions have impact on the combustion characteristics in a very complicated way. It has been found that the biomass addition to coal would improve the combustion efficiency because of the lower CO concentrations and higher char burnout level in co-firing. In addition, NO_x emission has been found closely linked to the flame stability, and SO_x emission reduced in general for all co-firing cases.

Kazagic and Smajevic [33] presented synergy effects found during the co-firing of wooden biomass with Bosnian coal types in an experimental reactor. The co-firing tests used spruce sawdust in combination with Kakanj brown coal and a lignite blend of Dubrave lignite and Sikulje lignite. Coal/biomass mixtures at 93:7 and 80:20 wt% were fired in a 20kW pulverized fuel (PF) entrained flow reactor. During the tests,the temperature in the experimental facility varied between 880 and 1550°C, while the excess air ratio varied between 0.95 and 1.4. There was sufficient combustion efficiency underall co-firing regimes, with burningout at 96.5–99.5% for brown coal–sawdust co-firing. Synergy effects were detected for all co-firing regimes with regard to SO_2 emission, as well for slagging at the process temperature suitable for the slag tap furnace. CO_2 emissions were also calculated for the blends tested and significant reductions of CO_2 found,due to the very low ranking of Bosnian coals. Finally, much lower NO_x emissions were measured at the lower process temperatures and the lower excess air ratio used in all co- firing regimes. It was not, however, possible to identify clearly the influence of the biomass content in the co-firing blend on NO_x emissions during the tests performed.

Munir *et al.* [34] investigated combustion behavior of sheameal-coal, cotton stalk/coal, sugar cane bagasse/coal, and wood chip/coal blends to realize their energy potential thermochemically in a 20 kW pulverized coal fired combustor. Biomass blending ratios of 5, 10, and 15% (thermal) were used in each set of experiments. It was found that agricultural residues have larger fractions of cellulose and acid cellulose hydrocarbons, which indicate less aromaticity as opposed to coal. It was found that co-combustion of agricultural residues with coal has a positive impact on NO_x, SO_2 reduction, and carbon burnout. The traditional slagging and fouling indices for coal ash fusibility displayed mixed results when applied to pure agricultural residue ash. Co-combustion of agricultural residues with coal seems more practicable than pure agricultural residues firing due to the potential risk of slagging and fouling. They suggested to develop corelations, specifically to predict ash fusibility behavior of different varieties of agricultural residues. Each of the samples studied displayed a significantly stronger release of volatility matter than pure coal during devolatilization. Biomass fuel nitrogen is known to form NH_3 in contrast to coal nitrogen which tends to form HCN. They recomened that co-combustion of agricultural residues with coal may have larger effects on NO_x reduction when operated under air and fuel staging conditions.

Zhang *et al.* [35] presented an overview of recent advances in thermo-chemical conversion of biomass. They dicussed the principles, reactions, and applications of four fundamental thermo-chemical processes (combustion, pyrolysis, gasification and liquefaction) for bioenergy production, as well as recent developments in these technologies. They have also discussed advanced thermo-chemical processes, including co-firing/co-combustion of biomass with coal or natural gas, fast pyrolysis, plasma gasification and supercritical water gasification. While discussing advantages and disadvantages, potential for future applications and challenges of these processes, they concluded that the co-firing of biomass and coal is the easiest and most economical approach for the generation of bioenergy on a large-sale because of the few modifications that are required to upgrade the original coal based power plants.

2.2 Biomass Combustion and Co-combustion in Fluidized Bed Reactors

Kuprianov *et al.* [36] reported an efficient and sustainable operation performance of the conical FBC when firing pre-dried Thai sugar cane bagasse in wide ranges of the combustor load and excess air. No effect of the static bed height (or sand amount in the combustor bottom) on the temperature-emission patterns was found in this work. The combustion efficiency was found to be in the range of 96 to 99.7% for firing the pre-dried bagasse in wide ranges of the operating variables. However, for this conical FBC operating on the maximum load, the highly efficient combustion (over 99%) at the minimized NO_x emissions could be achieved when the excess air was maintained at the 50–60% level. For the reduced combustor loads, the excess air could be diminished and maintained at the value corresponding to about 99% combustion efficiency.

Prompubess *et al.* [37] studied co-

combustion of coal and rice husk in a circulating fluidized bed combustor (CFBC). The effects of mixed fuel ratios, primary air and secondary air flow rates on temperature and gas concentration profiles along riser (0.1 m inside diameter and 3.0 m height) were studied. The average particle size of coal used in this work was 1,128 mm and bed material was sand. It was found that the temperatures along the riser were rather steady at about 800-1,000 degrees Celsius. The emissions of NO_x and SO_2 were found to be reduced in the co-combustion condition with an increases in the average bed temperature. Blending of coal with biomass, rice husk, did improve the combustion efficiency of coal itself even at low concentration of rice husk of 3.5 wt%.

Atimtay and Kaynak [38] investigated co-combustion of apricot and peach fruit stones in a bubbling fluidized bed combustor with a lignite coal, various ratios of biomass to coal ranging from 0 to100 wt.% were tested. For the peach stone co-combustion tests, efficiencies are about 98% and for the apricot stone co-combustion tests, efficiencies ranged between 94.7% and 96.9% for 25%, 50% and 75% of apricot stone in the fuel mixture. SO_2 emission of the ligniteis around 2400–2800 mg/Nm^3, whereas the biomass fuels havezero SO_2 emission. NO_x emissions are all below limits set by the Turkish Air Quality Control Regulation of 1986 (TAQCR).

Sun *et al.* [39] studied combustion characteristics of pure cotton stalk (CS) with 10–100 mm length have been studied in a CFB combustor. The fluidizing medium was alumina. Although as the fluidizing velocity is 4.5 m/s (N = 10.2), there will exist a little more segregation in the cold-state tests, yet the dense bed can keep steady state combustion for pure CS in the CFB. A fairly steady dense bed temperature between 830°C and 880°C has been obtained. Due to the high volatile content of CS, a significant amount of combustion takes place in the dilute phase. The results show that as the fluidizing velocity increases, the temperature of the dense phase decreases. Meanwhile, the temperature of the dilute phase increases and becomes more uniform. To assure combustion steady, the secondary air flow and gas flow to the loop seal should be controlled reasonably. The results show that SO_2 emission varies from 32 ppm to 55 ppm, and NO emission ranges from 110 ppm to 153 ppm at the basis of oxygen concentration of 6% in volume in flue gas. The highly efficient combustion, over 98.5%, of CS combustion in the CFB is achieved. In this study, the excess air ratio of around 1.3 and air split ratio of 1:0.88 was found to be optimum to provide high combustion efficiency of CS.

Ghani *et al.* [40] reported the results of rice husk and palm kernal combustion in coal fired fluidized bed combustor.Their experimental results gave combustion efficiencies of 60–80% and 80–83% for the mono-combustion of rice husk and palm kernel shell, respectively. An addition of a 50% mass fraction of coal increased the carbon combustion efficiency up to 20%. They found coal-fired fluidised bed boiler capable of burning agricultural residues with minimum modifications, such as air requirement and fluidising velocity.

Madhiyanon *et al.* [41] performed co-combustion tests in a cyclonic fluidized-bed combustor (FBC). The rice husk was used as primary fuel, while bituminous coal was employed as the supplementary fuel in the co-combustion experiments. As regards emissions, 260–416 ppm NO_x (at 6% O_2) appeared somewhat high and failed to comply with Thai co-combustion standards (<280 ppm). The comparatively great NO_x emissions arose from the high bed temperature (~1000°C); however, were comparable with bubbling FBCs. Although changes in the coal component had an immense effect on NO_x increases, occasionally the relationships were non-linear. In fact, operating conditions were crucial to NO_x development. NO_x formation can be lessened by either decreasing λ, or bed temperature, a consequence of increasing λ. The SO_2 emissions of 10–180 ppm (at 6% O_2) were considerably lower than Thai regulations (<236 ppm). CO increased with an increase in the coal fraction, and CO levels of 65–260 ppm (at 6% O2) were desirable for Thailand standards (<740 ppm). Maintaining well acceptable combustion efficiency and emissions (except NO_x), the thermal percentage of coal in the fuel mixture can reach 25%.

Youssef *et al.* [42] investigated the combustion of four kinds of biomass in a circulating fluidized bed. They found that the temperature distribution was not affected strongly by the excess air ratio for wheat straw and sawdust-wood combustion. The highest temperature level occurs at EA (excess air) = 1.24 for straw and sawdust while it occurs at EA = 1.4 for corncobs. The excess air ratio of 1.24 can be taken as an optimum value for minimum CO and NO_x emissions. According to the German environmental limits, the CO emissions were over the limit ($CO > 250$ mg/Nm^3) and the NO_x emissions were found to be under the limit ($NO_x < 300$ mg/Nm^3). The SO_2 emissions are very low (less than 20 mg/Nm^3) for all tested biomass fuels and hence they are under the limit ($SO_2 < 400$ mg/Nm^3).

Khan *et al.* [43] reviewd the potential of biomass combustion in fluidized bed boilers. They concluded that apart from small scale greenhouse or community boilers, the use of biomass as a sole energy source is unimaginable especially for electricity production. They recomended, the most feasible way of increasing the share of this sustainable energy fuel in world energy supply is through co-firing. Fuel based pollutants (NO_x, SO_x, dust and metal emissions), however, may need secondary measures. For NO_x, air staging together with SCR, SNCR, and reburning delivers high reduction rates (up to 95%). The lower sulfur content in most biomass makes SO_x emissions irrelevant. They concluded that a lot of work is needed to characterize biomass fuel. Development and standardization of reliable methods to characterize biomass fuel especially biomass ashes is of utmost importance for the successful future of sustainable fuel. Work on the reactor/combustor front is also essential for the plants to be commissioned in the future to make them more robust and adaptable to this renewable fuel class.

2.3 Biomass Combustion Characteristics

Christensen [44] described the mechanisms involved in ash formation in biomass combustion as shown in Figure 1.

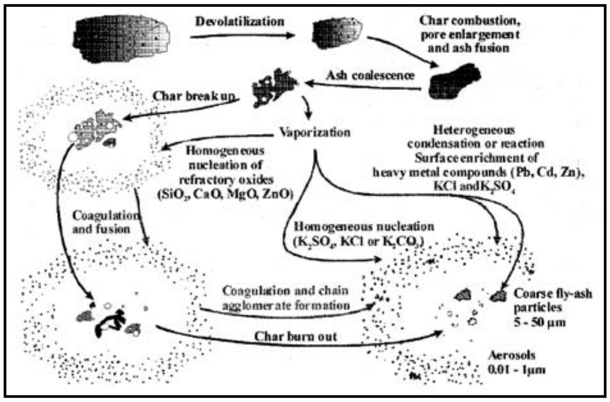

Figure 1. Mechanisms involved in ash formation in biomass combustion. (Source: Van Loo and Kopejan [45].

Jenkins *et al.* [46] reviewed and discussed various properties (composition, energy values, rates of combustion and pollutant emissions) of different biomasses like wheat straw, alfalfa stems, rice straw, olive Pitts, almond shells and urban wood etc which are important to the design and development of combustion and other types of energy conversion systems. They pointed out unavailability of the standard engineering practices for biomasses to which industry can refer. They stressed for the need of standardized engineering practice in sampling and analysis of the biomass and for the interpretation of the analytical data.

Bai [47] described the mechanism of wood chips combustion as shown in Figure 2.

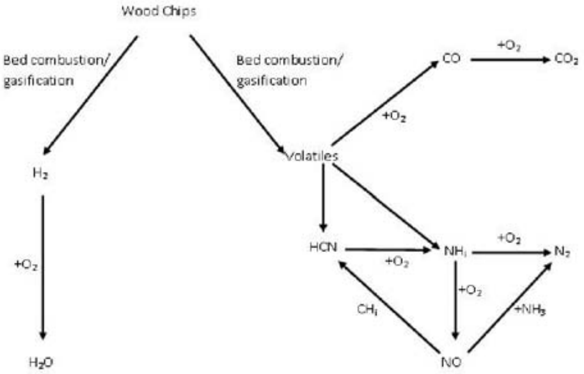

Figure 2. Mechanism of wood chip combustion.

Haykeri-Acma [48] investigated combustion characteristics of some biomass samples such as sunflower shell, colza seed, pine cone, cotton refuse and olive refuse with the help of non-isothermal thermogravimetry. The burning profiles derived by applying derivative thermogravimetry technique showed the difference in thermal characteristics (burning peak temperatures, maximum combustion rates, weight loss percentages etc) of the investigated biomasses.

Demirbas [49] revealed in his findings that biomass has significantly lower heating values than most coal and it is in part due to generally high moisture content and in part due to high oxygen content. The structural, proximate and ultimate analysis results of bio-waste differ considerably.The burning velocity of pulverised biomass fuels like sunflower, pinecone is considerably higher than that of coals.

Gani *et al.* [50] investigated the co-combustion characteristics of saw dust and low rank coal in an electrically heated drop tube furnace and found that biomass can enhance ignition characteristics of low rank coals due to high (VM) content in biomass. They elucidated that NO behaviour can be simulated by homogeneous reaction schemes. They found that NO and N_2O concentrations during co-combustion remained same as was in coal even if the input fuel-N for co combustion becomes half of that for coal combustion.

Ballester *et al.* [51] conducted a study to evaluate the impact of differences in fuel composition on flame characteristics, through measurement of the spatial distribution of the main parameters: temperature and concentrations of O_2, CO, NO_x, unburnt hydrocarbons, and N_2O. The higher volatiles content in the lignite led to higher temperatures and more intense combustion than the bituminous coal. Nevertheless, more marked differences were observed between the flames from the biomass and coals. The much higher volatiles content of the wood resulted in a more intense flame close to the burner. It was found that the combustion zone extended further for the biomass; while unburnt species were very low for the coals at an axial distance of 1 m, high values were detected for the pulverized oak. Their findings suggested that two stages can be distinguished in the biomass flame: a zone of intense combustion close to the burner, followed by a second region where the large biomass particles gradually devolatilize and are consumed.

Gani and Naruse [52] discussed the effect of cellulose and lignin content on the combustion characteristics of biomasses. They tested bagasse, palm oil fibre, rice straw and cornstalk in thermo-gravimetric analyzer. Their results suggested that cellulose content in the biomass may enhance the ignition characteristics and decomposition of lignin since the cellulose compounds have the structure of branching chain of polysaccharides and no aromatic compounds, which are easily volatilized. Consequently, the biomass will burn at the flowing steps. First, the cellulose components in the biomass are volatilized, so that the porosity in the char particles of biomass increases and that oxygen easily diffuses into the char particles. Then, the lignin components in the biomass can also react with oxygen diffused even if the reactivity of lignin itself is low.

Shanmukharadhya and Sudhakar [53] found that the pyrolysis kinetics of bagasse plays an important role in prediction of the thermal fields and ultimately stability of the furnace. This influence is particularly significant in the predicted delay to ignition of the fuel. Size and shape of the fuel also have a major influence in so far as the location and rate of deposition of the fuel on the grate. Their results showed that the fuel moisture content has a significant affect on the size of the pre-ignition zone and hence furnace stability.

Di Blasi [54] reviewed combustion and gasification rates of lignocellulosic chars. He reported that lignocellulosic chars are far more reactive than coals. She described that the rate of steam gasification of biomass is about 4–10 times greater than that of lignite, as a consequence of peculiar chemico-physical properties. The volatile content of lignocellulosic fuels (typically 80–90%) is at least twice that of coal. The hydrogen/carbon and oxygen/carbon molar ratios vary between 1.3–1.5 and 0.5–0.6, respectively (versus 0.8–0.9 and 0.1–0.3 for coals). Wood chars have porosities with values from 40 to 50% and pore sizes between 20 and 30 mm, whereas coals have porosities ranging from 2 to 18% and pore size around 5Å. Furthermore, the ash content is very low and the pore structure is highly directional, typical of that of wood and its intra-fiber cavities. Finally, she suggested further work for different feed stocks.

2.4 Air-staged Co-combustion of Biomass with Coal

Abbas *et al.* [55] tested sawdust-coal co-firing flames in a 0.5 MW furnace using dual-fuel burner . The introduction of sawdust as a secondary fuel enhanced the coal devolatilization rates within the near burner region. However, the effect of its introduction on the combustion and NO_x emission performance was found to be dependant on the near burner mixing mode.

Van De Kamp and Morgan [56] performed single burner experiments at the scale of 2.5 MW, with a swirl stabilised aerodynamically Air Staged Burner (AASB) in a boiler chamber simulator with internal dimensions of 2 x 2 x 6.3 m. The pulverised coals studied are bituminous coals of high and medium volatile content, and low and high sulphur content. The biomass fuels studied are straw and waste paper. The co-firing ratios varied from 0% to 100% straw. Different coals showed similar trends in NO_x and SO_2 emissions. The main parameters affecting the NO_x, SO_2 emissions and burnout were the co-firing ratio, coal type and flame type. Preferential burning (lower burnout) was observed in the 20-40 % straw/coal co-firing range and trends were different for high and medium volatile coal In addition, the effect of air and fuel staging on burner performance was also established. It was found that NO_x could be reduced by ~60% with fuel placement (i.e. by varying the mode of fuel injection), and by 70-80% with the introduction of air staging.

Hein and Bemtgen [57] rejected the idea of exclusive biomass firing and pointed out that an exclusive biomass utilisation would lead to the construction of many decentralized plants, which is time consuming and would require high financial investments as well because of the need for large storage capacities due to seasonal fuel availability. Co-combustion, in contrast, is considered to be the cheap option for utilising the existing biomass resources. They advocated co-combustion in industry due to ecological and economical advantages like conservation of fossil fuel resources, reduction of dependence on fuel imports, utilisation of agricultural and forest residues, reduction of emissions of harmful species from fossil fuel combustion, minimization of waste disposal. They suggested biomass excellently suited for the application of NO_x and SO_2 reduction in conjunction with air staging and reburning because of the high volatile content of the biomass. They reported the ignition and combustion tests of biomass co-combustion in pulverised mode carried out in various laboratory equipments (RWE, ICSTM, KEMA,), pilot plants ranging from 0.5-2.5 MW (RWE, IVD, ICSTM, KEMA, IFRF) and full scale boilers of 100 and 120 MW_e (ELSAM, VEAG). They found NO_x emissions level extremely sensitive with respect to biomass composition, co-firing ratio, injection mode, primary and reburn stoichometry. Biomass used were, straw, miscanthus and wood. They further anticipated reduction in NO_x emissions and recommended further investigation in this area to generate detailed data for optimization.

Spliethoff and Hein [58] investigated the effects of co-combustion of miscanthus, straw and municipal sludge together with primary fuel hard coal in pulverized fuel furnaces. A pulverized coal test rig (0.5 MW) was used for experimental results. The investigations revealed that biomass addition has appositive effect on emissions reduction and does not lead to increased CO emissions. They found air staging as an effective measure to reduce NO_x emissions in the case of straw, wood and miscanthus with optimum particle diameter. SO_2 emissions decreased with the addition of miscanthus, straw and wood but increased for sewage sludge with increasing biomass portion. They reported NO reduction of 77%,81% and 76% for thermal share of 10%, 25% and 40% of straw at primary stoichiometry 0f 0.7,0.65 and 0.6 respectively while keeping the primary zone residence time of 2.5 s.

Werther *et al.* [59] highlighted the use of agricultural residues in co-firing. He presented a review on the various issues associated with agricultural residues like low bulk density, low ash melting point, high volatile matter content and the presence of nitrogen, sulphur, chlorine and high moisture content. He recommended densification for effective storage and transportation .He anticipated low emissions of SO_2, NO_x from co-combustion of agricultural residues. Keeping in view of the high volatiles from the devolatalisation process of all agricultural residues and relatively high nitrogen content in some agricultural residues, he suggested staged combustion.

Slazmann and Nussbaumer [60] investigated the potential of air- staging for NO_x reduction in fixed bed 75kW furnace using wood with a low nitrogen content and UF-Chip board with high nitrogen content. They found NO reductions of 66% and 72% for wood chips and UF-chipboards respectivelyThey presented NO_x formation and destruction path as shown in Figure 3.

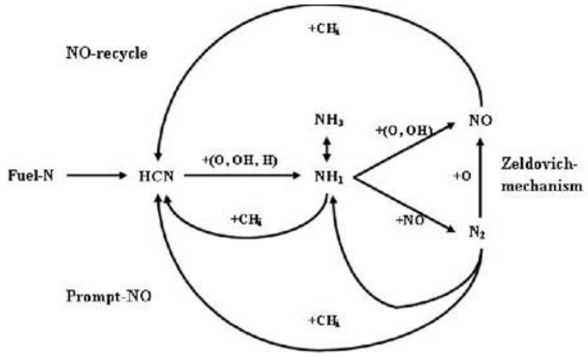

Figure 3 NO_x formation and destruction in gas phase.

Nussbaumer [61] described main reactions during two-stage combustion of biomass with primary air and secondary air as shown in Figure 4. He suggested biomass combustion has a need to be improved. He recommended herbaceous biomass and bio residues for investigations to fulfil future clean energy supply.

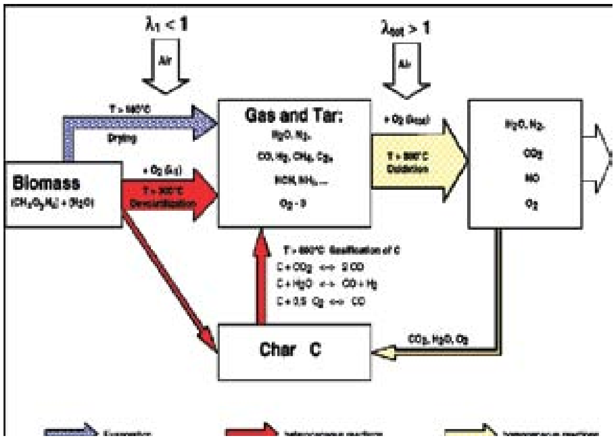

Figure 4. Reactions in two stage combustion of biomass.

Okasha [62] investigated the effects of air staging on the combustion performance of rice straw using an atmospheric bubbling fluidized bed combustor. The obtained results indicate that staged combustion appears an effective technique to reduce NO_x emissions, in particular, at higher operating temperatures. Typically, at 850°C bed temperature, NO_x concentration is reduced by about 50% when 30% of fed air is introduced as secondary air. Staged operation has a slight, non-monotonic effect on SO_2 emission. Combustion efficiency improves with increasing secondary air ratio reaching a maximum value that is mainly attributed to a reduction in fixed carbon loss. With further increase in secondary air ratio, combustion efficiency; however, decreases again since entrained fixed carbon and exhausted carbon monoxide tend to increase. The range of secondary air ratio, over which combustion efficiency improves, expands at higher operating temperatures.

Van Loo and Koppejan [45] described that drying and pyrolysis will always be the first steps in a solid fuel combustion process. The relative importance of these steps will vary, depending on the combustion technology implemented, the fuel properties and combustion process conditions. A separation of drying/pyrolysis/gasification and gas and char combustion, as in staged-air combustion, may be utilized. They described the combustion process of small biomass paricle as shown in Figure 5 .

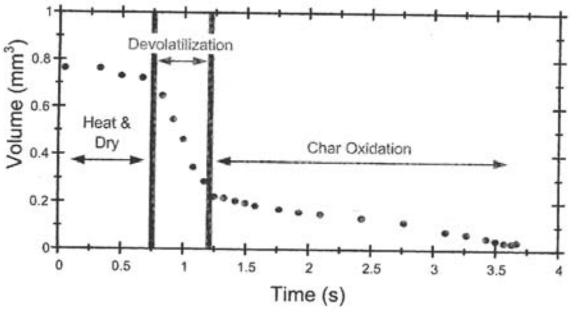

Figure 5. The combustion of small biomass particle proceeds in distinct stages.[45].

They further described that biomass fuels produce greater volatile yields than coals and, hence, they can create larger fuel rich regions than coal in near-burner region.Biomass fuels are,therefore,expected to enhance the performance of low NO_x burners.Biomass fuels may also have some potential as reburn fuels for NO_x reduction from coal combustion. In addition,biomass co-firing can also reduce NO_x.

Lin *et al.* [63] performed experiments in a suspension fired 20 kW laboratory-scale swirl burner test rig for combustion of biomass and co-combustion of natural gas and biomass. The main focus was put on the effect of two-stage combustion on the NO emission, as well as its effect on the incomplete combustion. They found significant reduction in NO emission in the case of two stage combustion. The experimental results showed that an optimal first-stage combustion stoichiometry (λ_1) of around 0.8 in the fuel-rich zone at which a minimum NO emission was achieved. When using wood and straw as co-firing fuels, 15-25% of the fuel-N was converted to NO. Straw appeared to give the lowest conversion of fuel-N to NO.

Munir *et al*. [64] investigated co-combustion potential of Shea meal, Cotton stalk, Wood chips and Sugar cane bagasse in a 20kW down-fired combustor under air-staging mode of operation. NO reductions between 49% to72% were obtained under optimum air-staged conditions of primary zone stoichiometry(SR_1) = 0.9. A 10 % biomass blending ratio (BBR) was found to be optimum for NO reduction with no adverse effect on fouling and slagging.They presented possible routes for NO_x reduction in two stage co-combustion of biomass with coal (Figure 6)

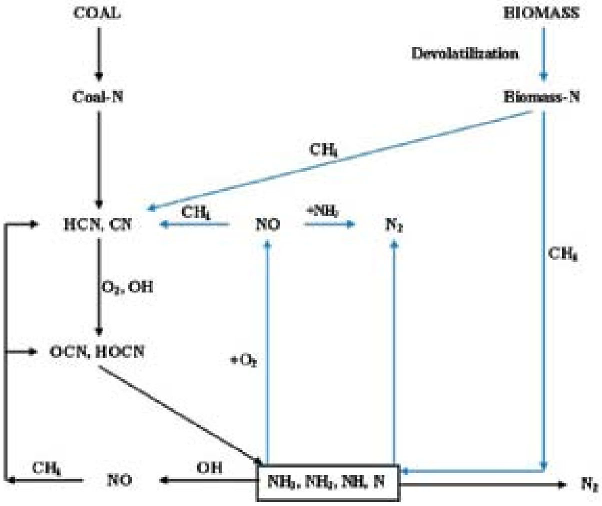

Figure 6. Possible routes for NO_x reduction during co-combustion of biomass with coal in the primary zone.

2.5 *Co-combustion using Biomass as Reburn Fuel*

Kricherer *et al.* [65] investigated NO_x reduction potential of different fuels under reburning configuration on a 0.5 MW (th) pulverized fuel rig. Coal, natural gas, straw and light fuel oil were used as reburn fuels. They found that NO, emissions could be reduced with gaseous, liquid and solid reburning fuels to minimum concentrations of 110-150 ppmv NO_2 (6 vol.%). They found volatile matter of reburning fuel, maximum-possible residence time, particle size of solid fuel and mixing conditions as effecting operating parameters for NO reduction in reburning.

Rudiger *et al*. [66] found that biomass (straw and sewedge sludge) pyrolysis gas mainly consists of CO, H_2 and C_xH_y. They used this gas as reburn fuel and obtained high NO_x reductions.

Rudiger *et al.* [67] found that blending of pulverized biomass (straw, miscanthus, wood) with coal showed a high burnout up to 20% thermal input of biomass for all particle sizes of the bio fuels tested. CO emissions remained below 100 mg/m^3 in the most cases. Reburn investigations with three pulverized biomasses resulted in NO_x emissions of approximately 300 mg/m^3 (6% O_2). With pyrolysis gas as reburn fuel, minimum NO_x emissions of 200 mg/m^3 (100 ppm) at 6% O_2 in the flue gas were measured. Best minimizing results were obtained with pyrolysis gas produced at about 800°C using coal as raw material; using biomass as feedstock, the influence of the pyrolysis temperature was not found significant. The nitrogen concentration, especially in the tar components of the pyrolysis gas, appeared to have a positive effect on NO_x reduction in the reburn zone of the combustion reactor.

Hansen *et al.* [68] studied co-firing of straw with coal in 150 MWe utility boiler: in situ measurements carried out in Denmark. The focus was on fly ash and high temperature corrosion. They did not quote any results. However they discussed the previous experience with 80 MW CFB, Boiler for 50% straw and 50% coal in the same context. They reported co-fired boiler performance associated with substantial uncertainties and recommended further tests of 2000-2500 h for corrosion analysis.

Adams and Hardings [69] evaluated the application of wood as reburning fuel in cyclone-fired Allen Station boiler in order to reduce NO_x. They found that maximum NO_x reductions of 45% were achieved with reburning zone stoichiometries less than 0.9 and increase in residence time increased the reduction. When the carrier gas was flue gas instead of air, NO_x reduction increases to 55%. They concluded that wood reburning is a viable option for reducing NO_x emissions in Allen Station boilers.

Maly *et al.* [70] evaluated reburning performance for the biomass and carbonized refuse derived fuel (CRDF), low rank coal, bituminous coal, coal pond fines and natural gas. The highest performance was obtained with biomass and CRDF, each of which has high volatiles, low nitrogen content, and high concentrations of sodium and potassium in ash. They found over 70% NO_x reduction achievable at a reburn heat input of 20%.

Harding and Adams [71] investigated hard wood and soft wood as reburn fuel in 38 kW down fired combustor and found that stoichiometric ratio in reburn zone is the single most important variable affecting NO_x reductions. At reburn zone stoichiometric ratio of 1, NO_x reduction up to 30% was achieved and at a scoichiometric ratio of 0.9-0.95, 40-50% NO_x reduction was measured. Whereas NO_x reductions as high as 70% were obtained at stoichiometric ratio of 0.85 in the reburn zone for 10-15% thermal input. They conducted a series of combustion tests at Reaction Engineering International to evaluate the potential for utilizing wood biomass as a reburn fuel for nitrogen oxides (NO_x) control. Two different biomasses, a hardwood and softwood, were evaluated as reburning fuels and compared to coal and natural gas. NO_x reduction fell to about 40-50% at slightly higher stoichiometric ratios ($0.9<SR<0.95$) and to 30% at stoichiometric ratios of approximately 1.0. The NO_x reduction was strongly dependent on initial NO_x concentration and only slightly dependent upon temperature, where increased temperature increased NO_x reduction. Finally, the experimental results suggest that wood is as effective as natural gas or coal as a reburning fuel.

Slazmann and Nussbaumer [60] found that biomass containing more nitrogen content performs better in reburning contrary to air-staging for NO_x reduction.

Casca and Costa [72] evaluated the effectiveness of the reburning process using biomass (rice husk) as reburn fuel in a large-scale laboratory furnace. For comparison purposes, tests were also conducted using natural gas and ethylene as reburn fuels. The effects of the reburn fuel fraction (energy basis), residence time in the reburning zone, and initial NO_x concentration for the three secondary fuels on NO_x reduction were investigated large scale laboratory furnace. They found that at reburn zone residence times of about 0.7 s the reburning performance of the rice husk (1) was comparable to that of the natural gas reburning at high reburn fuel fractions, with almost 60% NO_x reduction achievable at reburn fuel fractions of 25 and 30%, and (2) approached those of the natural gas and ethylene at high initial NO_x concentrations, with nearly 60% NO_x reduction attainable at initial NO_x concentrations between around 500 and 970 ppm. The results also revealed that there was a correlation between the extent of NO_x reduction and particle burnout: the higher the reduction, the lower the burnout.

Theis *et al.* [73] burned mixtures of peat with bark and peat with straw in a lab-scale entrained flow reactor that simulates conditions in the super heater region of a conventional biomass-fired boiler. The results indicated that it is possible to burn up to 30 wt% bark (renewable biofuel and pulp mill waste) and up to 70 wt% straw (renewable biofuel and agricultural waste) in mixtures with peat (CO_2-neutral fossil fuel) without encountering increased deposition rates.

Ballester *et al.* [74] performed tests in a semi-industrial-scale furnace to evaluate NO_x reduction potential of oak saw dust in co-firing applications when configured according to a reburning strategy. The range of the residence time in reburn zone was =0.41–1.44 s. The stoichiometry of reburn zone was varied from 0.85 to1.05. NO_x reductions were found to be about 4–10% lower than with natural gas.

3. Energy Crises and Pakistan

Pakistan is an energy deficient country. The per capita electricity consumption was 480 kWh in 2007–08. Over the same period, the world average per capita electricity consumption was about 2659 kWh, almost six times larger than that of Pakistan [75].

In 2008, Pakistan was facing an electricity deficit of over 4500 MW, a 40% of the total demand. This deficit could reach over 8000MW by 2010 [76]. Electricity demand in Pakistan will increase in the range of 12 MTOE to 17 MTOE by the year 2018, at an average growth rate of about 5% to 7% and will require installed capacity of about 35 GW to 50 GW [77]. Only 55% of the Pakistan's population has access to electricity. At present, the people are facing severe load shedding/blackout problems due to shortage of about 3 GW power supply. Gas and oil have 65% share in conventional electricity generation. Indigenous reserves of oil and gas are limited and the country heavily depends on imported oil. The oil import bill is a serious strain on the country's economy [78].

Pakistan must develop indigenous environment friendly energy resources to meet its future electricity needs. Pakistan can overcome this energy crisis by co-utilizing its un-used agricultural residues and coal reserves. This strategy can solve the energy crises while producing clean energy, deposing off waste and increasing income of the rural population.

Pakistan's 68 percent population live in villages and rely on agriculture for their sustenance. Total coal reserves of Pakistan are estimated to be around 187 billion tonnes. There is a great scope for large-scale utilization of coal in power generation. Already, a power plant of 150MW capacity using Lakhra coal has been completed in Sindh province [79]. Many developing countries like Pakistan, India, Ghana and Nigeria are located in the climate regions where large amounts of residues are available. Co-combustion of agricultural residues in energy recovery schemes could significantly increase the income of the people in these countries [4]. Agricultural residues are a form of biomass that is renewable but largely not utilised in the energy recovery schemes. The amount of crop residue produced in the world is estimated at 2802×10^6 Mg/year for cereal crops, 3107×10^6 Mg/year for 17 cereals and legumes, and 3758×10^6 Mg/year for 27 food crops. The fuel value of the total annual residue produced is estimated at 11.3×10^{15} kcal, about 7.5 billion bbl of diesel or 60 quads for the world [80]. Agricultural residues are non-edible plant parts that are left in the field after harvest. Co-firing of these abundantly available agricultural residues with coal can convert a negative value biomass in to a positive fuel along with environmental relief. If only 5% of coal energy could be replaced by biomass in all coal-fired power plants, this would result in an emission reduction of around 300 Mton CO_2/year [4]. The crop residue has theoretical energy potential of about 38.2 MTOE in Pakistan. Projections of energy potential of crop residues in Pakistan are given in Table 2.

Table 2. Projection of Energy Potential from Crop Residues in Pakistan.

Year	TEP (MTOE)
2005	35.5
2010	38.2
2015	41.1
2020	44.3
2025	47.7
2030	51.5

Source: [81]

In order to meet the growing power requirements of the industry, government has decided to develop co-power generation plants on fast track basis. In this regard the government has exempted such power plants from the fulfilling of pre-qualification criteria, submission of feasibility study and obtaining of Letter of Intent (LOIs) from Private Power Infrastructure Board (PPIB). Pakistan is the fifth largest sugarcane producer in the world with a production of 54 million tonnes. There are 83 sugar mills in the country having a potential to produce 2,000 MW electricity to national grid in the coming years. Co-generation projects will be based on bagasse (sugarcane waste) during the cane-crushing season (November-February) as main fuel whereas from March to October on coal as the main fuel**.** Sugar industry will be able to supply power to national grid during winter season when the hydel generation is at its lowest ebb. [82-84]. In order to utilize indigeneous renewable energy resources like biomass for power generation,the Senate of Pakistan has constituted an Act on May 25,2010 for the establishment of Alternative Energy Development Board [85].

Keeping in view the above elucidated scenario,the proximate and ultimate analysis of sugarcane bagasse, cotton stalk and coal from Pakistan (PC) were tested to explore their energy potential. The proximate and ultimate analysis of the samples along with HHV and bulk densities are presented in Table 3.

The bagasse samples used in this study ($SB_{S,}$ SB_T and SB_R) were collected from known sugar cane fields near, Shorkot city (South east Punjab), Faisalabad city (central Punjab) and Rahim yar khan city (South west Punjab) normally supplied to Kashmir sugar mills, Tandlianwala sugar mills and JDW sugar mills respectively. The Cotton stalk sample (CS) was obtained from agricultural field of Lodhran,

Table 3. Ultimate and Proximate analysis and HHV of the fuel samples (as received basis)

	CS	**SB_R**	**SB_S**	**SB_T**	**PC**
Volatile Matter (%)	73.10	68.23	71.72	62.81	43.59
Fixed Carbon (%)	18.00	17.11	11.70	13.86	33.98
Ash (%)	4.90	9.56	4.58	11.05	18.43
Moisture (%)	4.00	5.10	12.00	12.28	4
Carbon (%)	45.20	42.34	38.53	33.60	54.60
Hydrogen (%)	4.40	5.62	5.25	5.30	4.45
Nitrogen (%)	1.00	0.24	1.49	1.50	1.46
Sulphur (%)	0.00	0.001	0.00	0.00	4.96
Oxygen[a] (%)	40.50	37.13	38.15	36.27	12.1
Bulk density (kg/m^3)	310	180	140	160	560
HHV (MJ/kg)	17.70	17.37	15.67	11.80	26.22

[a] Calculated by difference

(Southern Punjab), Pakistan; cultivated during May-June season and handpicked in November-December season. Proximate analysis and ultimate analysis measurements were conducted using a thermo gravimetric analyser (Shimadzu TGA-50) and CE Instruments Flash EA1112 series, respectively . The proximate TG method involves heating the sample (under N_2) at a rate of 10°C/min to 110 °C then holding for 10 min to obtain the weight loss associated with moisture. The temperature is then ramped from 110 °C at a rate of 25°C/min to 910°C (under N_2) and held for 10 min to obtain the weight loss associated with volatiles release. Air is then introduced into the furnace chamber to oxidise the carbon in the char and the weight loss associated with this is the fixed carbon. The remaining material after combustion is the ash. The calorific values were determined by using a Parr 6200 oxygen bomb calorimeter.

3.1. A Feasible Solution for Cleaner Energy in Pakistan

Efficient management of agricultural waste is a growing issue in the countries with predominantly agricultural economies. These wastes are land filled and are a source of CH_4 release which is a greenhouse gas having 21 times higher global warming potential than CO_2 [14, 79, 86].

Amongst biomasses, agricultural residues (waste of food crops) have potential to be CO_2-neutral. During their growth as plants, they absorb carbon dioxide from the atmosphere and emit the same amount during combustion. Therefore, agricultural residues helps atmospheric carbon dioxide recycling and does not contribute to a net greenhouse effect [5, 10, 12, 14, 21, 22, 59, 16, 48, 87].

Both issues of agricultural waste management and pollutant emissions from existing coal power plants can be resolved simultaneously by utilising co-firing potential of agricultural waste. Biomass as a fuel class is very much different from coals. They have high volatile matter, higher hydrogen content, generally low nitrogen content and little or zero sulphur [14, 87]. As SO_2 emissions in the pulverized fuel firings strongly correlate with sulphur content of the fuel ,the net SO_2 emissions can be reduced by co-firing coal and biomass [21, 22, 26 ,58, 59]. As volatile matter (VM) content of biomasses is much higher than coals, a greater concentration of CHi radicals release from devolatalization process would enable us to utilise reductive power of the hydrocarbons as HC are known to react with NO_x to produce molecular N_2. Another anticipated advantage of this combination is the catalytic reduction of NO_x by NH_3. Since the volatile biomass fuel nitrogen preferentially forms NH_3 on pyrolysis in contrast to coal nitrogen which tends to form HCN, biomasses with slightly higher nitrogen content during reburning, could achieve NO_x reductions equivalent to those obtained by the addition of ammonia which is sometimes termed 'advanced reburning' [21, 58, 59]. As the fuel nitrogen released from biomasses ends up as NH_3 rather than HCN therefore N_2O is not a problem during the combustion of agricultural residues because later is responsible for N_2O emissions [59]. In the light of above discussion, it is anticipated that co-firing coupled with air and fuel staging techniques could improve NO_x reduction efficiency. Although it was mentioned by Hein and Bemtgen [57], Van loo and Koppejan [45] that due to high content of volatiles, biomass (agricultural waste residue) is well suited for application in NO_x reducing configurations such as air staging and reburning. Co-firing of agricultural residues with coal through in-furnace Air and Fuel Staged co-combustion techniques would not require costly process modifications in the existing coal-fired power plant.

The feasibility of using of biomass as a substitute fuel in coal fired power plants should be given due attention. It is expected to utilize biomass as a low-cost, substitute fuel and an agent to control emission. The opportunity for the adoption of this technology is quite attractive due to benefits associated. Successful development of technology to use biomass as supplement fuel will create an environment-friendly, low cost fuel source for the power industry and provide means for an alternate method of disposal of biomass and a possible revenue source for farmers and feedlot operators.

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