

Emissions and Furnace Gas Temperature for Electricity Generation via Co-firing of Coal and Biomass

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ABSTRACT

The emissions of carbon dioxide and nitrogen and sulphur oxides for electricity generation with coal and biomass co-firing are investigated and the furnace gas temperature assessed. The study uses simulation and considers fuel combinations based on two coals (bituminous coal, lignite) and four types of biomass (rice husk, sawdust, chicken litter, refused derived fuel). With increasing biomass, net CO₂ emissions are seen to decline significantly for all types of selected biomass, while gross carbon dioxide emissions increase for all blends except bituminous coal/refused derived fuel, lignite/chicken litter and lignite/refused derived fuel. The reductions in emissions of nitrogen and sulphur oxides are dependent on the contents of nitrogen and sulphur in the biomass. The results also show for all fuel combinations that increasing the biomass proportion decreases the furnace exit gas temperature.

KEYWORDS

Emissions, Furnace gas temperature, Biomass, Coal, Electricity generation, Co-firing.

INTRODUCTION

Various thermochemical and biochemical technologies exist for converting biomass into useful energy [1, 2]. Among these, biomass co-firing with coal is relatively common method which, according to some [3, 4], holds significant potential for fostering increased biomass utilization in the future.

The use of biomass/coal co-firing has expanded in recent years, particularly for electricity generation, due to its various advantages. These include fuel flexibility, an increased use of renewable energy sources in terms of biomass and the potential the co-firing approach for reducing greenhouse gas and other emissions.

Numerous studies [4-18] have been reported on biomass co-firing with coal. Researchers have summarized their experiences and reviewed the literature on co-firing in general studies [5-9] related to biomass co-firing. Experimental studies report into the effects of co-firing on factors such as boiler performance, combustion characteristics, and gaseous and particulate emissions. Modelling studies on biomass/coal co-firing have also

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been published. For instance, a numerical model for sawdust co-firing with coal in a 0.5 MW pulverized coal boiler has been developed by Abbas *et al.* [14] to investigate the influence of burner injection mode on burnout and NO emissions by utilizing the turbulence decay model for volatile combustion, the diffusive radiation model, and the $k-\varepsilon$ model. Backreedy *et al.* [15] report the modelling of a pulverized coal/pinewood co-firing process in a 1 MW combustor using a commercially available Computational Fluid Dynamics (CFD) code (Fluent version 6) to examine the impact of biomass particle size and shape on the burnout of blended char. Ghenai and Janajreh [16] apply CFD to a co-pulverized coal/wheat straw furnace to investigate the effects of co-firing on flow field, gas and particle temperature distributions, particle trajectories, and gas emissions. Huang *et al.* [17] examine the impact of coal co-firing ratio of biomass on energy efficiency, plant equipment, and gaseous emissions by using the ECLIPSE process simulator on a Pressurized Fluidized Bed Combustion (PFBC) combined cycle power plant. Dong *et al.* [18] model gasification based biomass co-firing, via a CFD analysis for a 600 MW tangential pulverized coal boiler.

Modelling studies on biomass/coal co-firing are less common than experimental studies, and thus are needed to help the technology develop and improve. This is, in fact, the main rationale for this article.

Additionally, numerous energy analyses of biomass co-firing pulverized coal electricity generation system and plant performance are reported in the literature [19]. Evaluation of slagging and fouling tendency and the related details for biomass and coal co-firing, the performance under oxygen enriched combustion conditions are also reported [20-22]. Advances in biomass co-firing with coal, the technology schemes, impacts and future perspectives have also been investigated [23].

Biomass co-firing based on a conventional pulverized coal electricity plant is modeled and assessed in this article, with the objective of improving understanding. Specifically, the impacts of biomass/coal co-firing on the furnace exit gas temperature and the gaseous emissions of CO₂, NO_x, and SO_x is investigated. Engineering Equation Solver (EES) is utilized in the analyses, and several combinations of fuels and co-firing conditions are considered to provide a comprehensive set of results. Engineering Equation Solver (EES) is a general equation-solving program that can numerically solve thousands of coupled non-linear algebraic and differential equations. The accuracy thermodynamic and transport property database provided for hundreds of substances in a manner that allows it to be used with the equation solving capability is a major feature of EES.

CO-FIRING SYSTEM

A diagram of the co-firing electricity plant analyzed and simulated in this article is shown in Figure 1. In the plant, there is a boiler, comprised of a combustor and heat exchangers (superheater and reheater). Also, there are two turbines: a High Pressure Turbine (HPT) and a Low Pressure Turbine (LPT). In addition, the plant has one Feedwater Heater (FWH) and two pumps: a Boiler Feed Pump (BFP) and a Condensate Pump (CP).

The schematic of the co-firing based power plant, modeled to facilitate the analysis, is presented in Figure 1. A direct co-firing configuration is employed because this is the most commonly applied co-firing configuration [24]. Pulverized biomass mixes with pulverized coal in the fuel transport lines before the burners because co-firing at elevated ratios can be achieved by this type of mixing [1]. Both air and the fuels enter the boiler at the environment temperature and pressure. Combustion takes place in the combustion chamber and the flue gases after exchanging heat with the feedwater exit through the stack. Superheated steam enters the high pressure turbine. After expansion through the first turbine, some of the steam is extracted from the turbine and routed to the open feedwater heater while the remaining is reheated to original temperature and expands

FUELS CONSIDERED

The analysis considers four biomass fuels: rice husk, pine sawdust, chicken litter, and refuse derived fuel, as well as two coals: bituminous coal and lignite. Information is presented in Table 2a for the biomass feedstocks and in Table 2b for the coals. The Higher Heating Value (*HHV*) of biomass and the Lower Heating Value (*LHV*) of coal are calculated as follows [1, 25]:

$$HHV_b = 0.3491C_b + 1.178H_b + 1.005S_b + 0.0151N_b - 0.1034O_b - 0.0211A_b \quad (1)$$

$$LHV_c = 427.0382n_c + 90.88110n_H - 207.46424n_O + 297.0116n_S \quad (2)$$

In equation (1), subscript *b* denotes biomass, while C, H, S, N, O, and A are the carbon, hydrogen, sulphur, nitrogen, oxygen, and ash contents of biomass in weight %. In equation (2), subscript *c* denotes coal, *n* is the number of moles of the respective constituent, and other terms are as defined earlier in equation (1). Equation (1) was developed using the calculated values of the lower heating value of numerous solid homogeneous organic compounds and it has an average deviation of 0.70%, while the validity of the equation (2) was established for fuels having wide of range of elemental composition and it has an average absolute error of 1.45%. Note that the higher and lower heating values are related for a substance:

$$HHV = LHV + 21.978n_H \quad (3)$$

Table 2a. Characteristics of selected types of biomass

Parameter	Biomass			
	Chicken	Pine	Refuse	Rice
Heating value [kJ/kg]				
Higher heating value	14,240	17,280	16,620	14,980
Lower heating value	13,410	16,180	15,410	13,990
Proximate analysis [wt%, as received]				
Fixed carbon	13.1	14.2	0.5	20.1
Volatile matter	43.0	70.4	70.3	55.6
Moisture	9.3	15.3	4.2	10.3
Ash	34.3	0.1	25.0	14.0
Ultimate analysis [wt%, as received]				
Hydrogen	3.8	5.0	5.5	4.5
Carbon	34.1	43.2	38.1	38.0
Oxygen	14.4	36.3	26.1	32.4
Nitrogen	3.50	0.08	0.78	0.69
Sulphur	0.67	-	0.33	0.06
Ash analysis [wt%]				
SiO ₂	5.77	9.71	38.67	94.48
Al ₂ O ₃	1.01	2.34	14.54	0.24
Fe ₂ O ₃	0.45	0.10	6.26	0.22
CaO	56.85	46.88	26.81	0.97
SO ₃	3.59	2.22	3.01	0.92
MgO	4.11	13.80	6.45	0.19
K ₂ O	12.19	14.38	0.23	2.29
TiO ₂	0.03	0.14	1.90	0.02
Na ₂ O	0.60	0.35	1.36	0.16
P ₂ O ₅	15.40	6.08	0.77	0.54

¹Vassilev *et al.* [26]

²Madhiyanon *et al.* [27]

Table 2b. Characteristics of selected coals

Parameter	Coal ¹	
	Bituminous	Lignite
Heating value [kJ/kg]		
Higher heating value	28,330	20,070
Lower heating value	27,340	19,070
Proximate analysis [wt%, as received]		
Fixed carbon	53.9	35.0
Volatile matter	28.2	44.5
Moisture	7.8	12.4
Ash	10.1	8.1
Ultimate analysis [wt%, as received]		
Hydrogen	3.9	4.1
Carbon	70.3	51.0
Oxygen	6.4	23.8
Nitrogen	1.07	0.4
Sulphur	0.41	0.16
Ash analysis [wt%]		
SiO ₂	51.67	46.15
Al ₂ O ₃	29.15	20.91
Fe ₂ O ₃	10.73	6.77
CaO	3.72	12.54
SO ₃	1.47	8.00
MgO	1.41	2.35
K ₂ O	0.29	1.49
TiO ₂	1.24	0.77
Na ₂ O	0.31	0.73
P ₂ O ₅	-	0.29

¹Vassilev and Vassileva [28]

ANALYSIS

The analysis focuses on the boiler, which is divided into two subsystems: combustor and heat exchangers (superheaters and reheater). The analysis is carried out for steady state conditions, so all components are taken to be operating at steady state.

Assumptions

All gases are ideal and ambient air is considered as 79% nitrogen and 21% oxygen on a volume basis. Excess air is used, and it is fixed at 20%, as recommended for the pulverized boilers [29]. The stack gas temperature is taken to be 150 °C [29]. Radiation and convective heat losses through large boilers and unburned losses due to combustibles in the ash are each 1.5% of the fuel energy input [29, 30]. Of the ash in the fuel, 80% exits as fly ash 20% and is collected as bottom ash [31]. The ash is inert and the bottom ash temperature is 600 °C, based on values reported for pulverized boilers with dry bottoms [29].

All components of the steam cycle have adiabatic boundaries and kinetic and potential energy effects are neglected. Each steam turbine is assumed to have an isentropic efficiency of 85% and each pump to have an isentropic efficiency of 88% [31]. The mechanical efficiency of each turbine and the generator efficiency are 99% and 98% respectively [31-33].

Methodology

In the analysis, the fuel flow rate remains the same and the calculations are on the basis of a unit fuel flow rate. The mass flow rate of coal at one particular co-firing

condition for all combinations of fuels remains constant. The mass flow rate of coal is decreased from 1 kg/s to 0.75 kg/s in intervals of 0.05 kg/s and that of biomass is increased from 0 kg/s to 0.30 kg/s. For all co-firing conditions, the operating temperature and pressure of all steam cycle components remain fixed. However, the mass flow rate of the steam produced varies at different co-firing conditions due to the changing feeding rate to the boiler which consequently changes the energy flows at the inlet and outlet of all components.

The co-firing share of coal (P_c) and the co-firing share of biomass, also named as co-firing ratio (P_b) are defined as:

$$P_c = [\dot{m}_c / (\dot{m}_c + \dot{m}_b)] \times 100\% \quad (4)$$

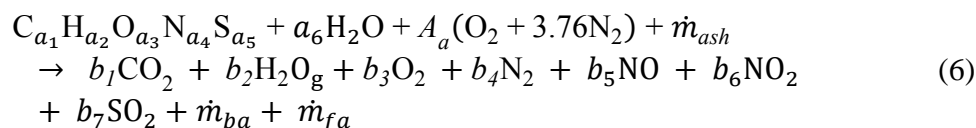
$$P_b = [\dot{m}_b / (\dot{m}_c + \dot{m}_b)] \times 100\% \quad (5)$$

Here, \dot{m}_c and \dot{m}_b respectively represent mass flow rate of coal and mass flow rate of biomass.

Abbreviations are used for the name of a fuel blend, based on the first letter of the coal and first and last letters of the biomass. For example, the abbreviation for the bituminous and rice husk blend is B/RH.

Combustion and emissions

The following general chemical reaction can be written for the combustion chamber, accounting for reactants entering and products leaving:



where A_a , \dot{m}_{ba} , and \dot{m}_{fa} denote the air molar flow rate, the bottom ash mass flow rate and the fly ash mass flow rate, respectively; a_1 to a_6 denote the molar flow rates of carbon, hydrogen, oxygen, nitrogen, sulphur, and moisture, respectively; and b_1 to b_6 denote the molar flow rates of the corresponding flue gases exiting the combustion chamber. Subscripts c and b denote coal and biomass, while the letters P and M represent the percent share of co-firing and molecular weight, respectively.

The mass flow rate of all reactants excluding air is found from the ultimate analysis and the molar flow rate of hot products and air are found by element balances, as described elsewhere [19]. All carbon in the fuel is converted to CO_2 . For pulverized coal boilers, the incomplete combustion loss is zero [29, 34]. Moreover, the addition of biomass in the blend enhances the combustion characteristics because of its high volatile content. NO_x emissions from the combustion process are mainly NO with a small fraction of NO_2 , usually less than 5% [34-37]. It is assumed that 96% of NO_x emissions are through the formation of NO and 4% are through NO_2 formation. 10-50% of the fuel nitrogen is normally converted to NO [35, 36]. 30% of the fuel nitrogen is assumed to convert to NO here. For a typical pulverized coal system, approximately 80% of NO emissions are due to fuel bound nitrogen [34] and NO emission through prompt mechanism is less than 5% [36]. The formation of NO emissions through prompt, thermal, and fuel bound paths are assumed to be 4%, 16%, and 80% of the total NO emissions formed respectively. Also, 30% of fuel nitrogen is assumed converted to nitrogen oxide. All sulphur in the fuel is oxidized to SO_2 , which is the only source of SO_x emissions. SO_x emissions are due to formation of SO_2 and SO_3 . However, sulphur

trioxide (SO_3) only constitutes 10% of SO_x emissions [34]. Both biomass and coal contain negligible amount of sulphur. So, if any traces of SO_3 are produced, they would be so small that they can be neglected.

Emissions factors

In determining the effects of co-firing on furnace exit gas temperature and gaseous emissions, two types of emission factors that represent normalized mass emissions are used to describe the effect of co-firing on emissions:

- Energy-based emission factors (in g/kWh). The energy-based factor represents the mass of emission per unit output (1 kWh) of electrical energy from the overall plant;
- Mass-based emission factors (in kg/t). The mass-based factor represents the mass of emission per unit mass of fuel input (1 t) to the overall plant.

For both cases, CO_2 emissions, gross (total) and net emissions are considered. The gross emissions include all material exiting the plant stack, while the net emissions are discounted by the CO_2 used in growing biomass and thus take into account the fact that biomass is relatively CO_2 neutral.

RESULTS AND DISCUSSION

The effects are investigated of biomass/coal co-firing on gaseous emissions and furnace gas temperature, considering four biomass (rice husk, pine saw dust, chicken litter and refuse derived fuel) and two types of coal (bituminous and lignite). The gaseous emissions are determined under various power plant operating conditions.

Effect of co-firing on furnace exit gas temperature

The furnace exit gas temperature is an important performance measure for the boiler as it affects heat transfer between the furnace exit gas and feedwater. Figure 2 shows that the furnace exit gas temperature decreases with increasing biomass content for all blends.

The extent of decrease in the furnace exit gas temperature is observed to depend on the heating value, the moisture content, and the ash content of biomass fuels. Biomass with a low heating value provides little energy input, and a high biomass moisture content necessitates that part of the heat supplied be used to vaporize the moisture. A high ash content results in more sensible heat leaving the combustion chamber with solid waste. These factors lower the furnace exit gas temperature.

Among the considered biomass types, chicken litter has the lowest calorific value and the highest ash content. It also contains more moisture than bituminous coal. Therefore, the largest reductions in furnace exit gas temperature are observed for the bituminous coal/chicken litter and lignite/chicken litter blends. When the co-firing ratio increases from 0% to 30%, for instance, the furnace exit gas temperature decreases from 2,079 K to 2,031 K for the bituminous coal/chicken litter blend and from 2,007 K to 1,962 K for the lignite/chicken litter blend.

The biomass moisture content is observed to affect the furnace exit gas temperature more significantly than the ash content. Refuse derived fuel has much higher ash content than sawdust, which has a much higher moisture content than refuse derived fuel. The higher moisture content of sawdust requires more heat to be supplied for the latent heat of vaporization during its combustion compared to refuse derived fuel. Hence, a more pronounced decrease in furnace exit gas temperature is observed for the bituminous coal/sawdust blend than for the bituminous coal/refuse derived fuel blend.

Similarly, lignite has higher calorific value and lower ash content than that of refuse derived fuel, but contains about 8% more moisture. Much more heat is needed to vaporize the moisture of lignite than of refuse derived fuel, diminishing the difference

between heating values of these two fuels. Thus, the furnace exit gas temperature decreases the least for the lignite/refuse derived fuel blend compared to all other blends. With respect to base coal, the furnace exit gas temperature decreases to 2,066 K and 2,004 K respectively for blends of bituminous coal/refuse derived fuel and lignite/refuse derived fuel, at a 30% co-firing ratio.

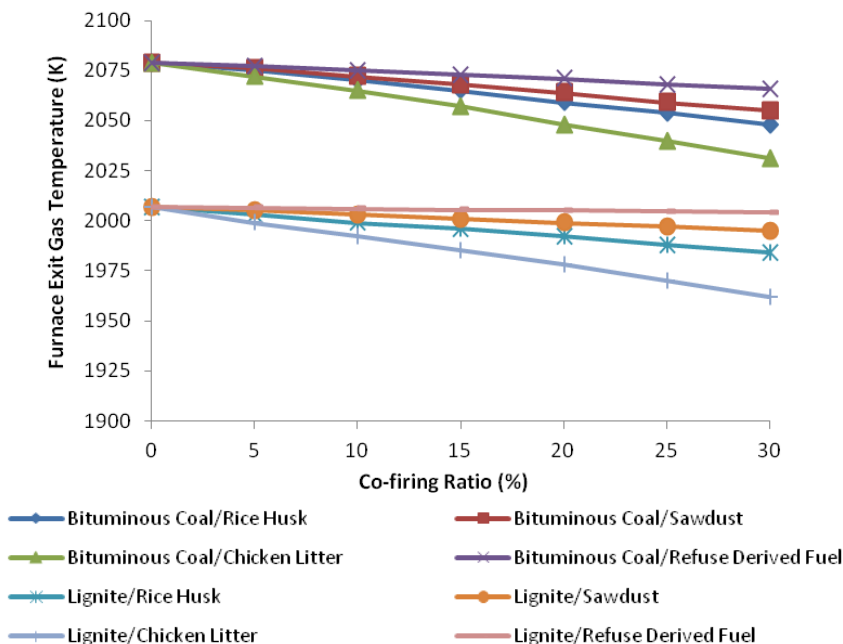


Figure 2. Effect of co-firing on furnace exit gas temperature

Effect of co-firing on emissions

Mass-based emission factors. The mass-based emission factors (with the listing for CO₂ representing gross emissions) are shown in Table 3a for blends of biomass and bituminous coal and in Table 3b for blends of biomass and lignite:

- Carbon dioxide:** The gross mass-based CO₂ emission factors (kg/t) found in all cases are less than CO₂ emission factors (3,125 kg/t for bituminous coal and 2,300 kg/t for lignite), suggested by the US Environmental Protection Agency [38]. Since biomass fuels have lower carbon content than coals, the mass-based CO₂ emission factors decrease for all blends as the biomass proportion increases in the blend. The most advantageous biomass in terms of CO₂ emissions reduction is chicken litter because it has the lowest carbon content of the considered biomass fuels. The mass-based CO₂ emission factor decreases by 15.4% and 9.9% respectively for the blends of bituminous coal/chicken litter and lignite/chicken litter when the co-firing ratio increases from 0% to 30%;
- Nitrogen oxide:** In all cases, except for chicken litter blends at high co-firing ratios (<20%), the mass-based NO_x emission factor is also less than NO_x emission factors (15.5 kg/t for bituminous coal and 7.5 kg/t for lignite) proposed by the US Environmental Protection Agency [38]. The mass-based NO_x emission factor decreases for all bituminous coal/biomass blends except bituminous coal/chicken litter. This is due to the fact that all considered biomass fuels except chicken litter have lower nitrogen concentrations than bituminous coal. Similarly, since all considered biomass fuels except sawdust contain more nitrogen than lignite, the mass-based NO_x emission factor increases for all lignite/biomass

blends except lignite/sawdust. Sawdust is the most beneficial biomass for reducing NO_x emissions because of its small nitrogen content. At a 30% co-firing ratio, the mass-based NO_x emission factor declines by 27.8% for the bituminous coal/sawdust blend and by 24.1% for the lignite/sawdust blend;

- *Sulphur oxide*: For the case of bituminous coal/biomass blends, the mass-based SO_x emission factor at all co-firing ratios is less than mass-based SO_x emission factor (around 13 kg/t for bituminous coal) suggested by the US Environmental Protection Agency [33]. However, in case of lignite/biomass blends, the mass-based SO_x emission factor is less than proposed emissions factor (around 5 kg/t for lignite) by the US Environmental Protection Agency [38] for rice husk and sawdust only. For bituminous coal and biomass co-firing, this factor decreases for all blends except bituminous coal/chicken litter because all selected biomass fuels except chicken litter have less sulphur content than bituminous coal. However, for lignite and biomass co-firing, the mass-based SO_x emission factor decreases for the blends of lignite/rice husk and lignite/sawdust, while this factor increases for the blends of lignite/chicken litter and lignite/refuse derived fuel. Sawdust is the most beneficial biomass in terms of SO_x reduction. The mass-based SO_x emission factor decreases at a 30% co-firing ratio by 30.0% and 29.8% respectively for the blends of bituminous coal/sawdust and lignite/sawdust.

Table 3a. Mass-based emission factors for various blends of bituminous coal and biomass

Fuel blend	Co-firing share [%]		Emission factor [kg/t]		
	P_c	P_b	CO ₂	NO _x	SO _x
Base ¹	100	0	2,839	10.08	9.03
B/RH	95	5	2,773	9.90	8.64
	90	10	2,708	9.72	8.26
	85	15	2,643	9.54	7.87
	80	20	2,578	9.36	7.49
	75	25	2,513	9.18	7.10
	70	30	2,447	9.00	6.72
B/SD	95	5	2,784	9.61	8.58
	90	10	2,729	9.15	8.13
	85	15	2,675	8.68	7.68
	80	20	2,620	8.22	7.22
	75	25	2,565	7.75	6.77
	70	30	2,510	7.28	6.32
B/CL	95	5	2,766	11.23	9.31
	90	10	2,693	12.37	9.60
	85	15	2,620	13.52	9.89
	80	20	2,547	14.66	10.18
	75	25	2,474	15.80	10.46
	70	30	2,401	16.95	10.75
B/RDF	95	5	2,774	9.94	8.94
	90	10	2,709	9.81	8.86
	85	15	2,644	9.67	8.76
	80	20	2,579	9.53	8.68
	75	25	2,514	9.40	8.59
	70	30	2,449	9.26	8.50

¹B/RH, B/SD, B/CL, and B/RFD denote respectively bituminous coal/rice husk, bituminous coal/sawdust, bituminous coal/chicken litter, and bituminous coal/refuse derived fuel

Table 3b. Mass-based emission factors for various blends of lignite and biomass

Fuel blend	Co-firing share [%]		Emission factor [kg/t]		
	P_c	P_b	CO ₂	NO _x	SO _x
Base ¹	100	0	2,062	3.77	3.52
	95	5	2,036	3.91	3.41
L/RH	90	10	2,009	4.04	3.30
	85	15	1,983	4.18	3.19
	80	20	1,957	4.31	3.08
	75	25	1,930	4.45	2.97
	70	30	1,904	4.59	2.86
	95	5	2,046	3.62	3.35
L/SD	90	10	2,030	3.47	3.17
	85	15	2,014	3.32	3.00
	80	20	1,998	3.17	2.82
	75	25	1,982	3.01	2.64
	70	30	1,966	2.86	2.47
	95	5	2,027	5.23	4.09
L/CL	90	10	1,993	6.69	4.65
	85	15	1,959	8.15	5.21
	80	20	1,925	9.61	5.77
	75	25	1,891	11.07	6.33
	70	30	1,857	12.53	6.89
	95	5	2,036	3.95	3.71
L/RDF	90	10	2,009	4.13	3.90
	85	15	1,983	4.31	4.09
	80	20	1,957	4.48	4.27
	75	25	1,931	4.66	4.46
	70	30	1,905	4.84	4.65

¹L/RH, L/SD, L/CL, and L/RFD denote respectively lignite/rice husk, lignite/sawdust, lignite/chicken litter, and lignite/refuse derived fuel

Energy-based emission factors. Figure 3a-3d shows the energy-based emission factors for all co-firing fuel blends:

- *Carbon dioxide:* The impact of co-firing, in terms of energy-based emission factors, is illustrated Figure 3a for total (gross) CO₂ emissions and in Figure 3b for net CO₂ emissions. The net CO₂ emissions account for the fact that biomass is considered to be CO₂ neutral. The trends shown for energy-based CO₂ emission factor agree with those of Kwong *et al.* [11] and Huang *et al.* [17];

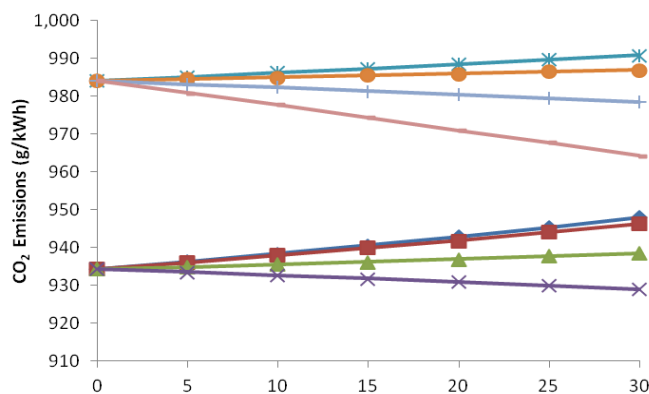


Figure 3a. Effect of co-firing on gross CO₂ emissions (legend as in Figure 2)

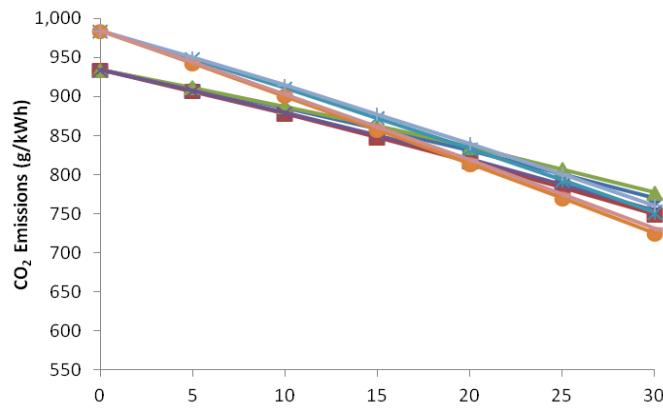


Figure 3b. Effect of co-firing on net CO₂ emissions (legend as in Figure 2)

- Nitrogen oxide:** The effect of co-firing on NO_x emissions is illustrated in Figure 3c. Since all biomass fuels except chicken litter have higher concentrations of nitrogen than lignite, NO_x emissions increase with co-firing ratio for all lignite/biomass blends except lignite/sawdust. For bituminous coal/biomass blends, however, regardless of the lower nitrogen concentrations of both rice husk and refuse derived fuel relative to bituminous coal, NO_x emissions increase slightly with co-firing ratio for blends of bituminous coal/rice husk and bituminous coal/refuse derived fuel. The increase in NO_x emissions is due to the decrease in net work output with increasing co-firing ratio. It is also evident that the most advantageous biomass in terms of NO_x reduction is sawdust because of its low nitrogen content. NO_x emissions decrease from 3.32 g/kWh to 2.75 g/kWh for the bituminous coal/sawdust blend and from 1.80 g/kWh to 1.44 g/kWh for the lignite/sawdust blend, as the co-firing ratio increases from 0% to 30%. The findings and observations regarding NO_x emissions found in this study agree with those of Spliethoff *et al.* [5], Kruczek *et al.* [10], Kwong *et al.* [11], and Huang *et al.* [17];

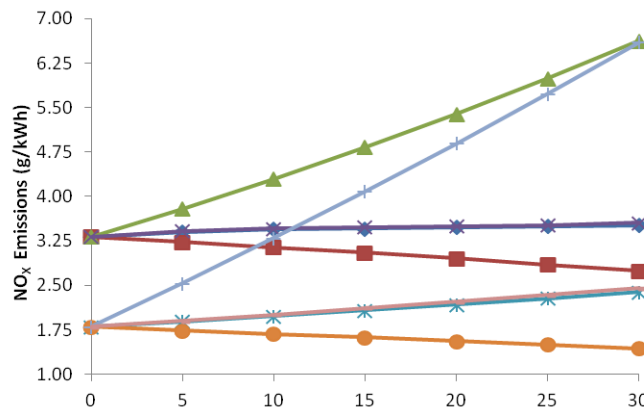


Figure 3c. Effect of co-firing on NO_x emissions (legend as in Figure 2)

- Sulphur oxide:** The sulphur content in fuel has a direct effect on the generation of sulphur dioxide during combustion. Among the chosen biomass, rice husk and sawdust have negligible sulphur content. So, their addition to a fuel mixture results in an overall reduction in SO_x emissions with co-firing ratio, as illustrated in Figure 3d. Since chicken litter has much higher sulphur content than bituminous coal and lignite, the SO_x emission factor increases with co-firing ratio for blends of bituminous coal/chicken litter and lignite/chicken litter. The sulphur

concentration of refuse derived fuel is slightly lower than that of bituminous coal. The SO_x emission factor increases with co-firing ratio for the bituminous coal/refuse derived fuel blend due to a decrease in the work output.

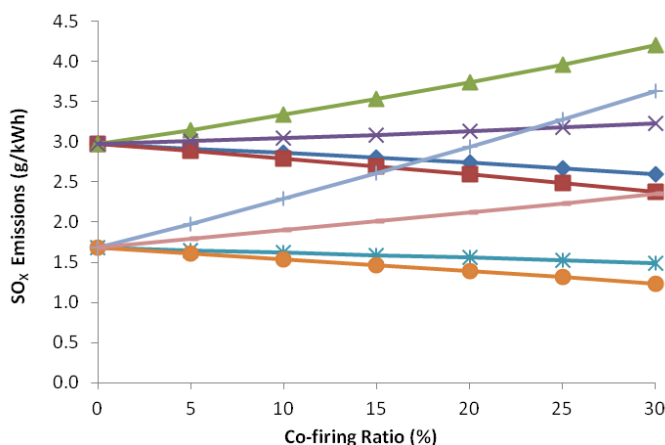


Figure 3d. Effect of co-firing on SO_x emissions (legend as in Figure 2)

The behaviours of the gross and net emissions of CO₂ differ, as follows:

- The gross CO₂ energy-based emission factor increases with co-firing ratio for all bituminous coal/biomass blends except bituminous coal/refuse derived fuel (see Figure 3a). In case of lignite/biomass blends, the gross CO₂ energy-based emission factor decreases with co-firing ratio for blends of lignite/chicken litter and lignite/refuse derived fuel and increases for blends of lignite/rice husk and lignite/sawdust. The increase in gross CO₂ emissions is due to the decrease in net work output with increasing co-firing ratio, which generally yields higher emissions compared with 100% coal. The decrease in CO₂ emissions with co-firing ratio for blends of bituminous coal/refuse derived fuel, lignite/refuse derived fuel and lignite/chicken litter is due to the relatively low carbon content of refuse derived fuel and chicken litter, which diminishes the work output reduction. The energy-based CO₂ emission factors at a 30% co-firing ratio are 948 g/kWh, 946 g/kWh, 937 g/kWh and 929 g/kWh respectively for blends of bituminous coal/rice husk, bituminous coal/sawdust, bituminous coal/chicken litter, and bituminous coal/refuse derived fuel. The corresponding CO₂ emissions factors are 991 g/kWh, 987 g/kWh, 979 g/kWh and 964 g/kWh for blends of lignite/rice husk, lignite/sawdust, lignite/chicken litter, and lignite/refuse derived fuel respectively;
- The co-firing process exhibits significantly lower net CO₂ emissions (see Figure 3b). With reference to base coal, net CO₂ emissions decrease from 934 g/kWh to 770 g/kWh, 749 g/kWh, 777 g/kWh and 754 g/kWh respectively for the blends of bituminous coal/rice husk, bituminous coal/sawdust, bituminous coal/chicken litter, and bituminous coal/refuse derived fuel, at a 30% co-firing ratio. The corresponding net CO₂ emissions for blends of lignite/rice husk, lignite/sawdust, lignite/chicken litter, and lignite/refuse derived fuel at a 30% co-firing ratio are 751 g/kWh, 725 g/kWh, 761 g/kWh, and 731 g/kWh respectively. The most suitable biomass in terms of CO₂ reduction is demonstrated to be sawdust due to it having the highest carbon content among the considered biomass fuels.

CONCLUSIONS

Biomass co-firing with coal has strong impact on furnace gas temperature and exhaust gas emissions. The biomass fuel, composition and co-firing ratio influences the

emissions from a electricity generation system, as do the biomass fuel and co-firing conditions. The present results clearly demonstrate the significant effect of biomass type and co-firing ratio on emissions and reduction in carbon dioxide. In fact, biomass co-firing with coal results in significantly reduced CO₂ emissions if biomass is considered to be CO₂ neutral. The gross (total) CO₂ emissions are lower if the carbon content of the biomass is relatively low. This characteristic also diminishes the work output reduction caused by biomass addition to a fuel blend. Also, reductions in NO_x and SO_x emissions are also achieved with biomass co-firing with coal if the selected biomass has less nitrogen and sulphur than coal. Therefore biomass co-firing can lead to substantial benefits in terms of CO₂, NO_x, and SO_x emissions reduction. Hence, co-firing of biomass with coal has significant environmental benefits and fosters an increased use of renewable energy.

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