

Article

Combustion Gas Emissions for Wood and Coal Cofiring on Grate Systems in Sub-Arctic Conditions

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Abstract

Wood and coal cofiring holds great potential for reducing greenhouse gas emissions from grate-fired combustion systems, as well as being widely technically feasible. This research was among the first to evaluate CO and NO_x levels within grate-fired cofiring at small utility scales. We evaluated two wood fuel types—high-quality aspen chips and lower-quality pellet mill residues. Each wood fuel was evaluated at two cofiring rates. Over 6 days of testing, CO contents ranged from 40 to 620 ppm, and NO_x contents ranged from 82 to 145 ppm. We found statistically significant differences in CO content when comparing low versus high cofiring rates, with high cofiring having greater CO concentrations. Relatively high CO emissions were attributed to greater moisture within the combustion chamber at higher levels of wood. Combustion efficiency versus cofiring rate was generally modeled the best as a quadratic relationship; carbon monoxide content versus cofiring rate was best modeled linearly. There were very few changes in combustion efficiency, fuel handling, or plant operation at the utility scale when cofiring at up to 15 percent of the energy value (versus no cofiring). From an operational standpoint, cofiring was relatively easy to implement and well received by plant managers.

Keywords: cofiring; biomass; wood residues; grate-fired; combustion gas; utility scale

1. Introduction

Wood and coal cofiring for electrical power generation has been recognized as a means of reducing greenhouse gas emissions versus combusting coal alone [1–3]. Internationally, cofiring coal and biomass has been conducted at nearly 200 power plants, with fuel types as diverse as wood chips, sawdust, switchgrass, and urban wood wastes [4]. Yet relatively few coal power plants cofire with biomass fuels on a regular basis. Most of the facilities that have conducted cofiring tests are large pulverized coal facilities and have considered a wide variety of fuel types and burner configurations [5–7]. However, in pulverized systems, both coal and biomass must be ground to a fine particle size, requiring substantial energy for fuel preparation, as well as additional screening and processing steps. These requirements can be reduced substantially when burning larger chips on grate-fired systems.

Biomass can provide wide-ranging benefits when combusted with coal, including potentially lower fuel costs, lower landfill disposal costs due to reduced ash generation, and reduced emissions of sulfur dioxide (SO₂) and oxides of nitrogen (NO_x) [8]. The potential drawbacks of cofiring include increased slag generation and fouling within the combustion



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chamber [9], increased fuel handling and storage requirements [10], and the potential for corrosion [11].

Many of the operating grate burners in the U.S. are part of aging power plants, approaching the end of their useful lives. Often, these systems are no longer at peak efficiency, especially when considering the coordinated operation of fans, fuel feed systems, combustion systems, grate assemblies, and emission control equipment.

In contrast to pulverized systems (which are designed for fine, powder-like fuel), grate burners are characterized by a high degree of flexibility and can handle diverse fuel types, moisture contents, and particle sizes. Further, grate systems allow solid fuels to rest on a fixed surface during combustion, providing greater (and more flexible) residence time. Cofiring biomass and coal at aging grate burners could be a feasible bridge strategy to reduce greenhouse gas emissions before decommissioning. Another advantage of grate-fired systems is that, when cofiring at low levels, existing equipment can be used with essentially no plant modifications needed [9]. This is in contrast to pulverized coal (PC) systems which typically require modifications to fuel handling, grinding, transport and conveying, and other components at costs of up to \$300 per kW [9]. Given these advantages of cofiring with grate-fired systems, there is a strong need to investigate the behavior of combustion gas emissions when cofiring.

The primary objective of this research was to measure combustion gas concentrations in stack emissions when cofiring two types of wood fuel, each at two cofiring ratios. We considered primarily CO (carbon monoxide) and NO_x (oxides of nitrogen) content versus various cofiring rates. We compared a high-quality, uniformly sized wood chip to low-quality manufacturing residue containing a wider distribution of particle sizes.

Most past research has been conducted on cofiring with different feedstocks and combustion systems. Numerous studies have considered the combustion gas sampling of biomass and coal in grate-fired systems. Due to the complexity and fuel requirements of conducting utility-scale tests, much of this past work has been either for short durations, in a laboratory setting, or sometimes at the residential scale. Although larger pulverized coal systems have been studied in detail [6,12], very little past work has been conducted on smaller grate burners (typically less than 50 MW).

Of these studies, very few have considered biomass and coal cofiring. Ross et al. (2002) [13] evaluated the concentrations of CO, CO₂, SO₂, and NO_x in addition to numerous polycyclic aromatic hydrocarbons (PAHs) when combusting coal and biomass in a fixed bed furnace. The emission factors of compounds such as SO_x, NO_x and toxic metals were significantly lower for pine sawdust than for coal.

Internationally, more than 20 biomass fuel types have been tested in grate boilers, including wood, coconut shells, dried sewage, grape wastes, olive husks, sugarcane residues, and switchgrass [12]. Others have developed models to predict emissions from rice straw [14], wheat straw, willow, miscanthus, and canary grass [12]. Municipal solid wastes can also be combusted in grate systems; however, advanced air management techniques may be needed [15]. Thus, grate combustion systems are flexible in terms of their operation and fuel types. However, grate-fired systems that experience incomplete combustion can have elevated emissions of CO, tar, poly aromatic hydrocarbons, and incompletely burned char [16].

Serrano et al. (2014) [17] evaluated combustion gases from the combustion of pine chips in a 50 kW boiler, comparing them to pine pellets. They considered the emissions of CO, O₂, and NO_x, as well as combustion efficiency and ash generation, over test periods of 6 h. They found that increases in secondary combustion air had no significant influence on efficiency but were effective in reducing CO emissions.

Sefidari et al. (2014) [18] measured the concentration profiles of O₂, CO, and NO in a 12 MW reciprocating grate boiler. They compared standard wood chips (including bark) with a “greenery fuel” which also included fresh branches and conifer needles (for a total of about 30 tons). They found that overall, there were no significant differences between fuel types for CO and O₂; however, there were localized differences in NO and NO_x emissions, which were higher for the fuel containing branches and needles. This could be attributed to higher inherent nitrogen concentrations in these fuel components and/or higher combustion temperatures.

Rogaume et al. (2009) [15] used a fixed bed reactor to study the influence of excess air on the combustion products of solid fuel. Much of their work involved measuring combustion profiles over 10 min periods. They found that NO_x concentrations were strongly influenced by the level of primary air and that total excess air below 2.4 was conducive to good mixing in the primary and secondary combustion zones. Although these studies were conducted on residential-scale burners, they are still relevant to the current study of utility-scale power plants, since the same combustion gases (mostly CO and NO_x) contribute to air quality issues in non-attainment zones.

Razmjoo et al. (2014) [16] considered the gas composition and temperature in a 4 MW reciprocating grate boiler. They also measured O₂, CO, and NO_x concentrations in gas streams, finding differences in concentrations between primary and secondary combustion chambers. Houshfar et al. (2011) [8] considered the combustion of demolition wood residues under staged air and non-staged air conditions in a laboratory setting. They found that the primary air ratio was the most important factor influencing NO_x emissions and that temperature combustion temperature was not a key variable as long as it was kept below 1000 degrees C. Over temperature ranges of 850–1000 degrees C, they found that CO emissions were inversely related to temperature.

Munir et al. (2011) [19] studied the influence of staged air to reduce NO_x emissions when cofiring with five different biomass types. When considering biomass thermal fractions of 5, 10, and 15 percent, they found that the 10 percent level was optimal for use with air-staging. Li et al. (2009) [20] considered gas concentrations above the grate for a utility-scale boiler. They compared two different loadings (28 and 18 tons per hour), finding differences in CO and NO in the fuel burning zone, as well as the displacement of and shifting in the fuel burning zone.

These studies and others illustrate that biomass and coal combustion gas parameters have been evaluated at scales ranging from the lab scale to the residential scale to the power plant scale. Many of these tests lasted between one and four hours and sampled parameters such as combustion efficiency, NO_x, SO_x, and CO. However, few studies have considered multi-day utility-scale tests with woody biomass on grate burners, where location-dependent processes within the combustion chamber such as gas reactions, ignition, combustion, and burnout can greatly influence emissions. Further, few studies have considered the feasibility of cofiring wood manufacturing residues, often available at lower costs and having minimal fuel processing requirements. The current research extends past efforts by evaluating combustion gas behavior over a range of realistic cofiring levels, operating conditions, and fuel types. We do so in sub-arctic conditions, where winter air quality conditions can be unique and challenging, requiring innovative approaches to wood fuel procurement, storage, and handling.

2. Materials and Methods

2.1. Site Description

The research test facility was the Aurora Power Plant (Fairbanks, Alaska), a 32-megawatt (MW)-capacity electrical generating plant. This plant burns approximately

210,000 tons of coal per year, acquired via railroad from the Usibelli Coal Mine near Healy, Alaska (approximately 110 miles from the power plant). This source is the only coal mine in Alaska and features coal known for its very low sulfur content, as well as its relatively low heating value. Net electrical generation is close to 180,000 MW-hours per year [21]. The Aurora plant also provides steam and hot water for a district heating system serving downtown Fairbanks. The facility employs one spreader stoker and two gravity feed systems at their three combustion units.

An additional feature of interior Alaska is the desirability for clean burning fuels, especially during winter months, when temperatures as low as -50 degrees F result in diminished air quality, inversions, and the formation of “ice fog” which tends to settle on populated valley floors. Thus, a motivation for our research was to evaluate incomplete combustion products that could impact local air quality.

2.2. Fuel Descriptions

For testing period 1, we cofired quaking aspen (*Populus tremuloides*), a low-density hardwood, with an average specific gravity of 0.42 at 12 percent moisture content [22]. Approximately forty green tons of aspen logs was reduced to 1-inch square chips at a nearby wood pellet facility. Wood fuel moisture content was about 28 percent (green basis). For testing period 2, wood product manufacturing residues were procured from the same pellet facility. This material represented lower-value white spruce (*Picea glauca*) wood not suited for pellet manufacture. Particle dimensions were more heterogeneous, ranging from approximately 1 to 3 inches in maximum dimension. By cofiring these two types of wood fuel, we were able to sample a high-quality fuel and a waste residue fuel, which included diverse product values, fuel morphologies, and combustion behavior.

Coal was obtained from a mine in central Alaska and was delivered by rail. This coal is characterized by its very low sulfur content, high moisture content, and relatively low energy content compared to many coals mined in the continental U.S. The average dimensions of coal particles were comparable in size to wood fuel, facilitating mixing and conveying. Coal moisture content and sulfur, ash, and volatile contents are indicated in Table 1. A total of 6 testing days were completed, which fully utilized both the aspen chips and manufacturing residues that were available.

Table 1. Daily coal characteristics during utility-scale cofiring tests on a grate system.

Day	Energy Content (BTUs per Pound)	Moisture Content (Percent)	Ash Content (Percent)	Volatile Content (Percent)	Carbon Content (Percent)	Sulfur Content (Percent)
1	7806	27.3	7.5	35.6	29.6	0.13
2	7891	26.5	7.8	35.8	30.0	0.14
3	7891	26.5	7.8	35.8	30.0	0.14
4	7710	26.7	9.2	35.5	28.6	0.14
Average	7825	26.6	8.1	35.7	29.5	0.13

2.3. Fuel Storage and Handling

For the wood–coal cofiring trials, essentially no operational changes were needed for fuel storage and handling compared to the use of coal only. Wood fuel was stored on an uncovered pavement pad within the power plant grounds, over an area of approximately 30 ft. by 30 ft. From the storage area, wood was loaded by a front-end loader into a fuel hopper where it was mixed with coal until a uniform mixture was achieved. The bulk wood and coal mixture was then transported via conveyor within the power plant to the combustion chamber. The fuel was deposited into a gravity-fed fuel bin and then metered into the combustion chamber.

2.4. Combustion Gas Sampling

The independent variables for this research were the cofiring rate and wood fuel type (each evaluated at 2 levels). The dependent variables were combustion gases, including carbon monoxide (CO), nitrogen oxides (NO_x), and oxygen (O₂), as well as combustion efficiency. We measured these with a portable hand-held combustion gas analyzer, sampling at 2 min intervals for each cofiring condition. We evaluated combustion gas parameters for a baseline of 100 percent coal (i.e., no cofiring), followed by either high or low cofiring rates. Baseline periods lasted at least one hour. We measured combustion gases from a point at the base of the combustion stack on the roof of the power plant. This was the most expedient place to do so and contrasts with other studies [23,24] that obtained measurements from inside the combustion chamber. The Aurora Power Plant has a series of 11 baghouse filters, used to trap particulate emissions within a fabric matrix. Since all of our combustion gas sampling occurred at a point upstream from the baghouse, the measurement probe was exposed to particulates entrained within the gas flow. From a practical standpoint, this did not influence our results but required the frequent changing of filters.

Since this was a utility-scale test, there was no way to precisely measure the cofiring rate in real time. We estimated the cofiring rates of wood and coal by first taking hourly samples during cofiring tests. We then separated wood from coal and weighed samples to determine initial weight. We determined the oven dry wood weight from separate samples. Coal moisture content data was provided by Aurora Power, based on average values per railcar. In the first series of tests, we cofired aspen chips at rates of up to 5 percent of the energy value. Since there were no operational problems noted, we decided to increase the cofiring rate to a maximum of 15 percent for the second round of tests (using manufacturing residue). We employed the linear regression and quadratic regression methods when evaluating trends between 3 levels of independent variables.

3. Results and Discussion

3.1. Operational Issues with Cofiring

During cofiring, we observed generally very good operations for fuel mixing, conveying, and combustion. However, at higher cofiring rates, we noted a somewhat uneven distribution of wood across the grate. This could have been attributed to the separation of wood and coal in the storage bunker, a large gravity-fed hopper located just prior to the conical section. It is possible that the wood fuel had a greater tendency to aggregate on the vertical sides of the bunker (versus the coal which was more “fluid”, tending to settle further down in the fuel bin). However, when fuel was sampled from conveyor belts, prior to the fuel bin, it was often the case that wood and coal were still very evenly mixed. Recent research has noted the benefits of oscillating combustion, employing an oscillating air supply [12] as well as the use of flue gas recirculation to reduce NO_x emissions [11].

The high aspen moisture content likely influenced combustion properties, particularly at high cofiring ratios. The particle geometry of the aspen chips (thin and uniformly sized) likely influenced wood fuel behavior throughout mixing, conveying, and combustion. This was especially true any time the aspen chips became part of an airstream such as in the combustion chamber. Thus, a disadvantage of having high-quality wood chips (which would have different particle geometry from the coal) could be an increased tendency to separate from coal during conveying and combustion or any time fuels were pneumatically carried. By contrast, the manufacturing residue became separated somewhat during processing and transportation, hindering the high levels of cofiring. This separation was attributed primarily to the geometry of the fuel, which was less compact and more “fluffy” than that of the aspen chips. With regard to combustion emissions, we found that although fuel mixing was generally excellent, both conveying and combustion were facilitated by

having a uniform fuel mix which resulted ultimately in a uniform distribution of fuel types across the grate surfaces. One issue not addressed in this research, since cofiring was conducted in spring and autumn months, was the need for covered and possibly heated wood fuel storage to avoid wood fuel freezing solid at winter temperatures sometimes reaching -50 degrees F.

3.2. Combustion Gas Composition

3.2.1. Carbon Monoxide

Carbon Monoxide Versus Cofiring Rate

Carbon monoxide is a product of incomplete combustion and is often inversely correlated to combustion efficiency and the level of air circulation [25]. This general relationship was observed during our cofiring tests. Consistent with [23], our research found that greater biomass cofiring rates lead to greater CO emissions, likely due to the higher volatile content of biomass versus coal. We also expect that the greater moisture content of biomass was also responsible for incomplete combustion on the fuel bed and higher CO levels.

We also found that the mean CO concentrations were lower when burning coal only versus any other cofiring conditions, including aspen chips and manufacturing residue (Table 2). This relationship held for both low and high cofiring levels. CO levels were higher for both fuel types when cofiring at about 5 percent cofiring rates (Table 2). In fact, CO levels were more than twice as high for cofiring at about 5 percent than with coal-only combustion. For aspen chips, we observed a clear linear trend between CO levels and cofiring rate over the three cofiring levels. The mean CO at the highest cofiring level for aspen (4.8 percent) was more than double that of control samples, with an R-squared value of 0.4775.

Table 2. Mean carbon monoxide (CO) content of combustion emissions, for all groups, with cofiring rates of up to 15 percent.

Wood Fuel Type	Cofire Rate	Number of Observations	Mean CO Content (ppm)
aspen chips	0 (coal only)	309	103.2
aspen chips	2.4	534	172.4
aspen chips	4.8	567	240.2
manufacturing residue	0 (coal only)	320	101.1
manufacturing residue	5	385	247.5
manufacturing residue	15	1051	192.6

These findings are in agreement with [24], which observed that CO and moisture fluctuations were well correlated with one another in the combustion zones, especially at the upper surfaces of the combustion bed. We also found clear trends of increasing CO content as the cofiring ratio increased between 0 and 5 percent for aspen chips (Figure 1, Table 2). At the high cofiring rate, the mean CO contents for aspen chips were more than twice those for combustion with coal only. Similarly, with manufacturing residue, CO contents were approximately twice as high for high cofiring versus combustion with coal only (Figure 2, Table 2). We suggest that this was due to the higher moisture content of the aspen chips, resulting in greater fluctuations in combustion gas composition.

We modeled CO concentration versus cofiring rate using linear, quadratic, and exponential models for aspen chips and manufacturing residue (Table 3). The results indicate very little difference between the three models for aspen chips (all had R-squared values from about 0.47 to 0.49). In general, our research found that CO and cofiring rates were more strongly correlated for aspen chips than for manufacturing residue (Table 3, Figures 1 and 2). However, for manufacturing residue, CO versus cofiring rate was mod-

elled the best as a quadratic relationship (R-squared of 0.28), with other models having even lower R-squared values. This is consistent with [13], which found non-linear relationships for CO concentrations.

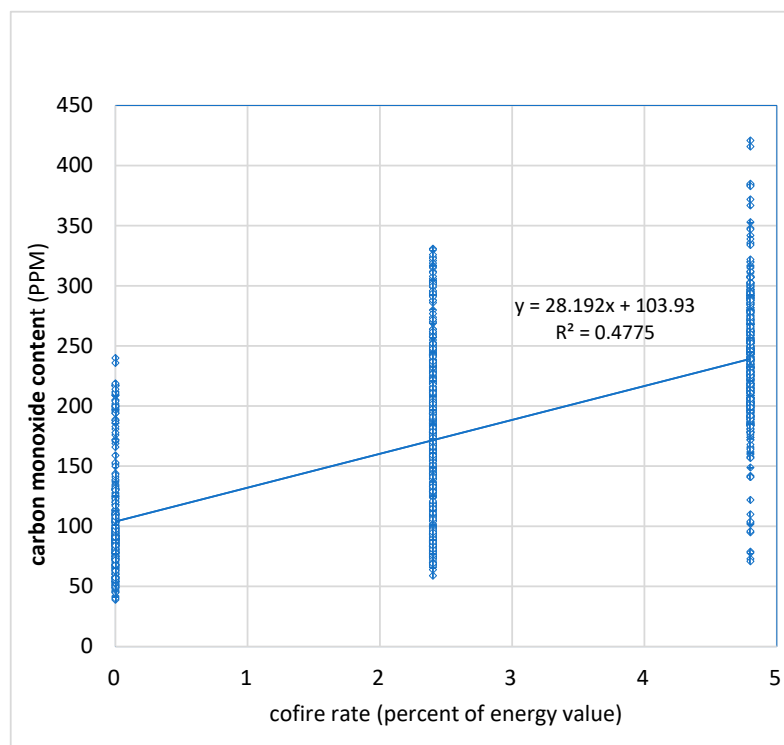


Figure 1. Scatterplot of carbon monoxide content versus cofiring rate for aspen chips, cofired on grate burner system at 2.4 percent or 4.8 percent of energy value (the squares represent individual observations while the line represents the best-fit regression line).

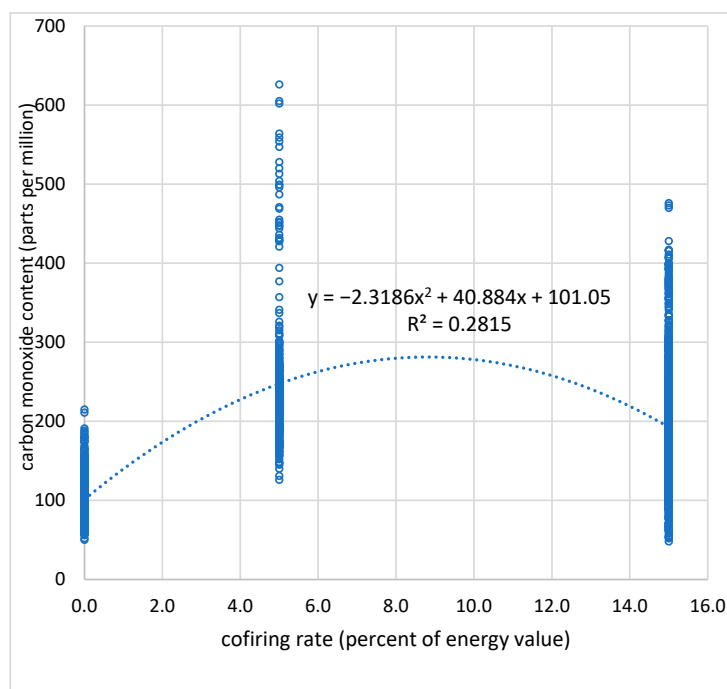


Figure 2. Scatterplot of carbon monoxide content versus cofiring rate for manufacturing residue, cofired on grate burner system at 2.4 percent or 4.8 percent of energy value. (the circles represent individual observations while the dashed lines represents the best-fit curvilinear regression).

Table 3. Modeling of carbon monoxide and NO_x versus cofiring rate for high-quality and low-quality cofiring feedstocks.

	Fuel Type	Modeled as	R-Squared	Best-Fit Equation
CO versus cofire rate	aspen chips	linear	0.4775	$y = 28.192x + 103.93$
	aspen chips	quadratic	0.4776	$y = -0.2302x^2 + 29.362x + 103.24$
	aspen chips	exponential	0.4916	$y = 98.366e^{0.1843x}$
	manufacturing residue	linear	0.0385	$y = 2.7693x + 160.08$
	manufacturing residue	quadratic	0.2815	$y = -2.3186x^2 + 40.884x + 101.05$
	manufacturing residue	exponential	0.0717	$y = 137.4e^{0.0204x}$
NO _x versus cofire rate	aspen chips	linear	0.0112	$y = -0.646x + 118.79$
	aspen chips	quadratic	0.2945	$y = 2.2373x^2 - 13.309x + 129.79$
	aspen chips	exponential	0.0094	$y = 118.22e^{-0.005x}$
	manufacturing residue	linear	0.0015	$y = 0.0553x + 107.89$
	manufacturing residue	quadratic	0.1995	$y = 0.2155x^2 - 3.4869x + 113.38$
	manufacturing residue	exponential	0.0013	$y = 107.54e^{0.0005x}$

Carbon Monoxide Versus Combustion Efficiency

We found that carbon monoxide concentrations in the stack gases varied from about 50 ppm to more than 400 ppm under the complete range of cofiring tests for manufacturing residue (Figure 3a–c). Several trends were apparent in our research. First, CO varied considerably less for coal-only combustion (Figure 3a) versus cofiring at either 5 or 15 percent (Figure 3b,c). Second, there was a small positive relationship between combustion efficiency and carbon monoxide at the 5 percent cofiring level (Figure 3b). Third, at the 15 percent cofiring level, there was a clear negative relationship between CO and combustion efficiency (Figure 3c). We suggest that this could be attributed to the amount of fuel moisture in the combustion chamber at the higher cofiring rate.

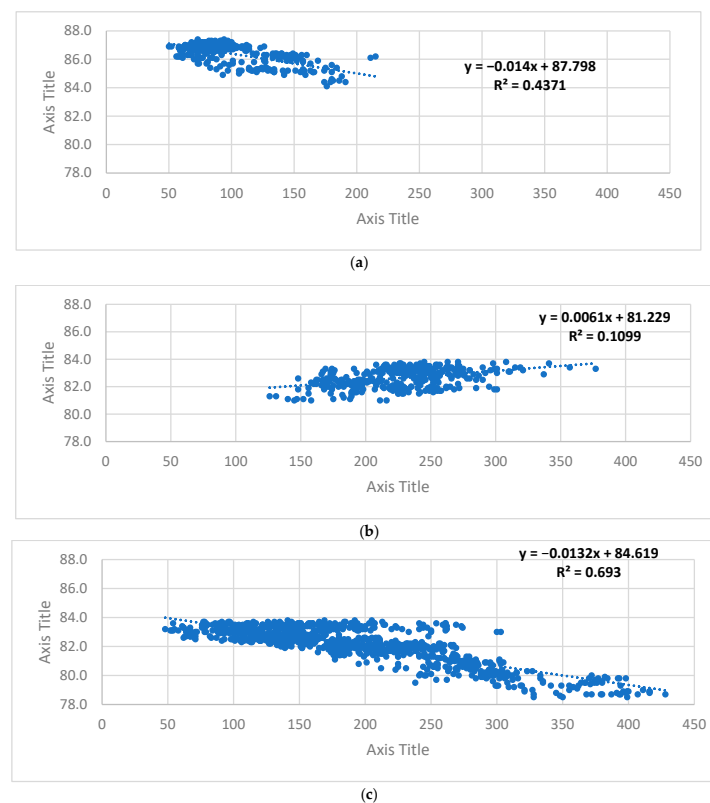


Figure 3. (a) Combustion efficiency versus carbon monoxide content for control tests (coal only). (b) Combustion efficiency versus carbon monoxide content for manufacturing residue (5 percent cofiring). (c) Combustion efficiency versus carbon monoxide content for manufacturing residue (15 percent cofiring).

3.2.2. Nitrogen Compounds

Lower combustion temperatures when cofiring with biomass can lead to NO_x reductions versus burning coal alone. This is observed since thermal nitrogen and the nitrogen inherent in the woody biomass both contribute to total NO_x emissions [26]. Some tests indicated a greater than 1 percent reduction in NO_x compounds for each 1 percent increase in the cofiring level [6]. Others found that cofiring up to 7 percent biomass can lower NO_x emissions by as much as 15 percent; however, this is dependent on the burner arrangements [27]. Li et al. (2012) [28] found that NO_x emissions associated with cofiring decreased with increasing ratios of biomass and the increased recirculation of flue gases. In the current study, we found that NO_x versus cofire rate was modeled the best under a quadratic relationship for both aspen chips (Figure 4) and manufacturing residue (Figure 5). In both cases, the minimum NO_x values were realized at intermediate cofiring rates. NO_x values were statistically higher with coal-only combustion versus intermediate or high levels of cofiring (Table 4).

Table 4. Mean NO_x content of combustion emissions, for all groups, with cofiring rates of up to 15 percent.

Wood Fuel Type	Cofire Rate	Number of Observations	Mean NO _x Content (ppm)
aspen chips	0 (coal only)	309	125.2
aspen chips	2.4	534	110.7
aspen chips	4.8	567	116.6
manufacturing residue	0 (coal only)	320	113.4
manufacturing residue	5	385	101.3
manufacturing residue	15	1051	109.6

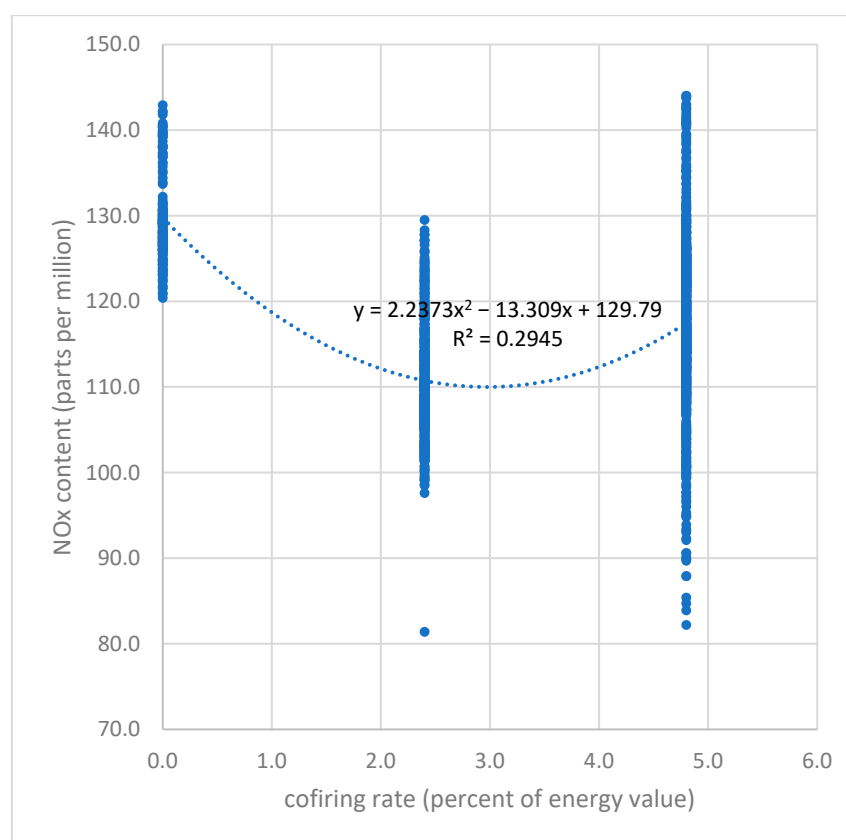


Figure 4. Scatterplot of NO_x content versus cofiring rate for aspen chips, cofired on grate burner system at either 2.4 percent or 4.8 percent of energy value.

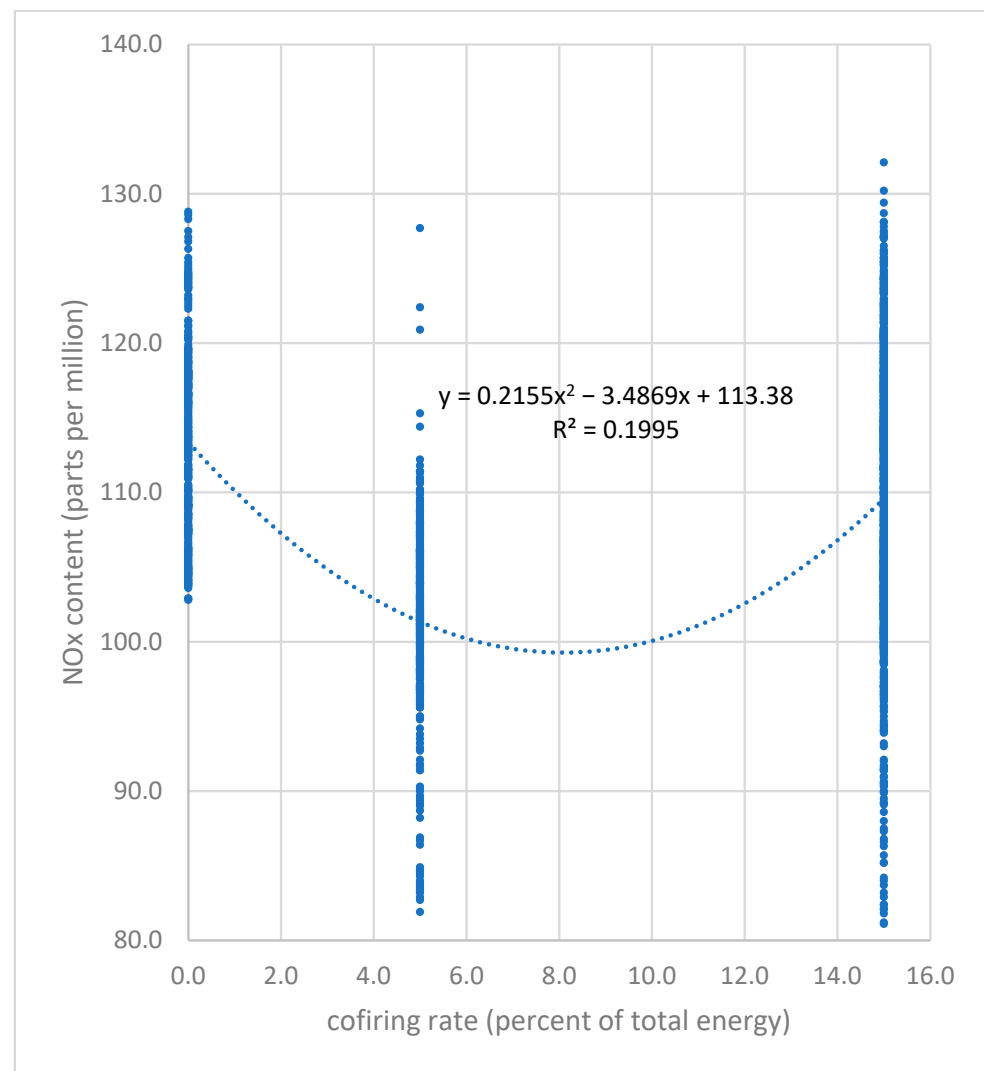


Figure 5. Scatterplot of NO_x content versus cofiring rate for manufacturing residue, cofired on grate burner system at 5.0 or 15.0 percent of energy value.

3.2.3. Combustion Efficiency

Past research found that only minor reductions in combustion efficiency occur when cofiring at ratios of up to 15 percent biomass by energy value [6]. Other research found that wood composite board and sawdust feedstocks, when included at levels of less than 20 percent of total energy, generally enhanced combustion performance while reducing emissions [23]. When we evaluated CO versus combustion efficiency at low cofiring rates, the two were poorly correlated (R-squared value of 0.10) (Figure 3b). However, for higher cofiring rates (15 percent), this correlation was much higher (R-squared value of 0.69) (Figure 3c). This trend was perhaps the clearest finding of our research and illustrates the challenges of detecting consistent relationships between variables at the utility scale. However, combustion efficiency tended to be higher when burning coal only (averaging about 86 percent) versus either 5 percent or 15 percent cofiring. Combustion efficiency versus cofiring rate for manufacturing residue was best modeled as a quadratic relationship, with very little variation between the 5 percent and 15 percent cofiring rates (Figure 6).

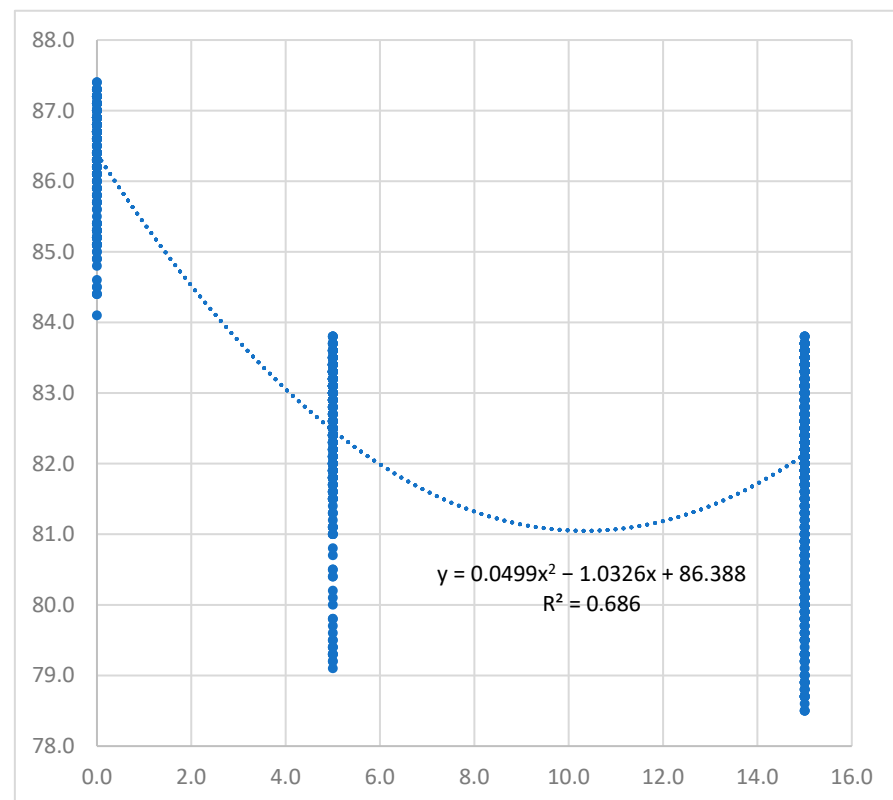


Figure 6. Combustion efficiency versus cofiring rate for all manufacturing residue samples.

3.2.4. Integrated Discussion—Combustion Gas Evaluations

We also observed a general increase in CO and a reduction in NO_x when burning larger fractions of wood with coal. It is hypothesized that the increased moisture content of the aspen chips (vs. coal) resulted in more evaporation and steam production inside the combustion chamber. As a result, more incomplete combustion (leading to greater CO levels) and lower combustion temperatures (leading to lower NO_x levels) were apparent. Cofiring with woody biomass could become an effective means of NO_x emission reduction for Aurora Power since they do not employ staged burning, selective catalytic reduction, or other measures sometimes used in coal facilities.

Perhaps the clearest trend we observed was the inverse relationship between combustion efficiency and carbon monoxide for manufacturing residue at the 15 percent cofire rate (Figure 3c). Here a correlation of -0.693 suggested a clear inverse relationship, with lower CO values at higher combustion efficiencies. In general, higher cofiring rates—due to a greater volume of wood and water—allowed for clearer trends compared to lower cofiring rates, which were often similar to coal-only conditions. This behavior could be influenced by temperature and gas interactions within different regions of the combustion chamber. Sefidari et al. (2014) [18] observed differences between different combustion zones in the freeboard region of the furnace, using numerous measurement ports. This finding was apparent when comparing the oxygen-rich region closest to the grate to the mixing region higher in the chamber (where drying, devolatilization, and char combustion can occur). Kubacki et al. (2012) [29] observed synergies between coal and biomass during combustion but also suggested that biomass type and volume can influence both the pyrolysis behavior of coal and the rate of volatile gas generation from coal. Ge et al. (2024) [6] found that air ratios during coal-spreading in combustors influenced both NO_x levels and fuel burnout properties. Although our research measured gas concentrations farther downstream (at the stack), it is possible that the gas dynamics mentioned above also influenced our readings.

This research was limited in that it was conducted in a utility-scale setting, and therefore we had only limited control over certain parameters. Ideally we would have liked to conduct additional tests at different cofiring levels, for longer durations. This was especially true for the aspen chips, which we tested at a maximum cofiring rate of about 5 percent of the energy value (versus 15 percent for manufacturing residue). However, due to the high cost of these chips, as well as the limited fuel storage area at the power plant, it was not feasible to use longer test periods or higher cofiring rates. Further, the aspen cofiring tests were conducted first, and plant managers were more comfortable “testing the waters” with lower cofiring rates (i.e., 5 percent of energy value or lower). For the manufacturing residue tests, conducted later, plant managers were comfortable cofiring at the 15 percent rate. These circumstances illustrate some of the challenges of cofiring at the utility scale, even for smaller grate systems such as the one evaluated in the current study.

4. Conclusions

Grate-fired combustion will continue to be important for the many smaller utilities still in use. This research, conducted at a sub-arctic power facility in Alaska, demonstrated the technical feasibility of cofiring coal and woody biomass at levels of up to about 15 percent of the energy value. We also found that facility operation was smooth and unhindered for all cofiring tests. However, the lower-value hog-fuels, which were less uniform in size, were somewhat more difficult to convey through the plant due to their irregular particle geometry. Combustion efficiency was generally strongly related to the CO content of the exhaust gases while being somewhat less directly related to NO_x content. We also found that CO and NO_x both exhibited different trends during cofiring (versus coal combustion only), and these properties were the most evident at high cofiring rates. In general, higher cofiring rates—due to a greater volume of wood and water present in the fuel mix—allowed for clearer trends compared to the lower cofiring rates that displayed characteristics similar to coal-only conditions. Given the northern location of the power plant (latitude 65 degrees north), and the problems in maintaining air quality during mid-winter months when “ice fog” is present, reduced NO_x levels could provide tangible benefits. However, notable challenges could be the outdoor storage of wood fuel in sub-freezing temperatures and the logistics of handling and conveying frozen wood. This research lays the groundwork for additional cofiring research with grate-fired coal plants, especially at high cofiring ratios, as well as mixtures of varying wood fuel quality, where the influence of wood moisture could be an overriding concern. Building upon this exploratory study, future research could include longer testing periods with additional fuel types, cofiring levels, and overall system sizes.

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Data Availability Statement: Source data supporting the reported results can be found by sending an e-mail to David Nicholls (david.l.nicholls@usda.gov).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Agbor, E.; Zhang, X.; Kumar, A. A review of biomass co-firing in North America. *Renew. Sustain. Energy Rev.* **2014**, *40*, 930–943. [CrossRef]
2. Backreedy, R.I.; Fletcher, L.M.; Jones, J.M.; Ma, L.; Pourkashanian, M.; Williams, A. Co-firing pulverized coal and biomass: A modeling approach. *Proc. Combust. Inst.* **2005**, *30*, 2955–2964. [CrossRef]
3. Boylan, D.M. Southern company tests of wood/coal cofiring in pulverized coal units. *Biomass Bioenergy* **1996**, *10*, 139–147. [CrossRef]
4. Carroll, J.; Finnan, J. Emissions and efficiencies from the combustion of agricultural feedstock pellets using a small scale tilting grate boiler. *Biosyst. Eng.* **2013**, *115*, 50–55. [CrossRef]
5. Fournel, S.; Marcos, B.; Godbout, S.; Heitz, M. Predicting gaseous emissions from small-scale combustion of agricultural biomass fuels. *Bioresour. Technol.* **2015**, *179*, 165–172. [CrossRef] [PubMed]
6. Ge, Z.; Kuang, M.; Qi, S.; Chen, J.; Wu, X.; Xie, W. Effect of the coal-spreading air on airflow and low-NO_x combustion within a 75 t/h coal-fired grate furnace. *Appl. Therm. Eng.* **2024**, *256*, 124076. [CrossRef]
7. Golden Valley Electric Association. 2019. Available online: <https://www.gvea.com/> (accessed on 20 September 2019).
8. Houshfar, E.; Skreiberg, O.; Løvas, T.; Todorovic, D.; Sørum, L. Effect of Excess Air Ratio and Temperature on NO_x Emission from Grate Combustion of Biomass in the Staged Air Combustion Scenario. *Energy Fuels* **2011**, *25*, 4643–4654. [CrossRef]
9. Hughes, E.E. Utility Coal-Biomass Cofiring Tests. In *Proceedings of the Advanced Coal-Based Power and Environmental Systems Conference*; U.S. Department of Energy National Energy Technology Laboratory: Pittsburgh, PA, USA, 1998; p. 4.2.
10. International Energy Administration Bioenergy Task 32, International Cofiring Database. 2010. Available online: <http://www.ieabcc.nl/database/cofiring.php/> (accessed on 20 September 2019).
11. Jancauskas, A.; Buinevicius, K. Combination of Primary Measures on Flue Gas Emissions in Grate-Firing Biofuel Boiler. *Energies* **2021**, *14*, 793. [CrossRef]
12. Jolibois, N.; Gehrmann, H.J.; Aleksandrov, K.; Hauser, M.; Stapf, D.; Jäger, B.; Wirtz, S.; Scherer, V.; Pollmeier, G.; Danz, P.; et al. Oscillating combustion of different fuel types for NO_x reduction in grate furnaces and coal burners. *Fuel* **2023**, *340*, 127504. [CrossRef]
13. Ross, A.B.; Jones, J.M.; Chaiklangmuang, S.; Pourkashanian, M.; Williams, A.; Kubica, K.; Andersson, J.T.; Kerst, M.; Danihelka, P.; Bartle, K.D. Measurement and prediction of the emission of pollutants from the combustion of coal and biomass in a fixed bed furnace. *Fuel* **2002**, *81*, 571–582. [CrossRef]
14. Kær, S.K. Numerical modelling of a straw-fired grate boiler. *Fuel* **2004**, *83*, 1183–1190. [CrossRef]
15. Rogaume, T.; Jabouille, F.; Torero, J.L. Effect of excess air on grate combustion of solid wastes and on gaseous products. *Int. J. Therm. Sci.* **2009**, *48*, 165–173. [CrossRef]
16. Razmjoo, N.; Sefidari, H.; Strand, M. Characterization of hot gas in a 4 MW reciprocating grate boiler. *Fuel Process. Technol.* **2014**, *124*, 21–27. [CrossRef]
17. Serrano, C.; Portero, H.; Monedero, E. Pine chips combustion in a 50 kW domestic biomass boiler. *Fuel* **2013**, *111*, 564–573. [CrossRef]
18. Sefidari, H.; Razmjoo, N.; Strand, M. An experimental study of combustion and emissions of two types of woody biomass in a 12-MW reciprocating-grate boiler. *Fuel* **2014**, *135*, 120–129. [CrossRef]
19. Munir, S. A Review on Biomass–Coal Co-Combustion: Current State of Knowledge. *Proc. Pak. Acad. Sci.* **2010**, *47*, 265–287.
20. Li, Z.; Zhao, W.; Li, R.; Wang, Z.; Li, Y.; Zhao, G. Combustion characteristics and NO formation for biomass blends in a 35-ton-per-hour travelling grate utility boiler. *Bioresour. Technol.* **2009**, *100*, 2278–2283. [CrossRef] [PubMed]
21. Nicholls, D.L.; Patterson, S.E.; Uloth, E. *Wood and Coal Cofiring in Interior Alaska: Utilizing Woody Biomass from Wildland Defensible-Space Fire Treatments and Other Sources*; USDA Forest Service: Washington, DC, USA, 2006.
22. The Wood Database. 2019. Available online: <https://www.wood-database.com/quaking-aspen/> (accessed on 20 September 2019).
23. Wang, Y.; Liao, Y.; Chen, Y.; Bin, Y.; Ma, X. Co-combustion of coal and composite board sawdust: Combustion behaviors, ash slagging characteristics, and gaseous pollutant emissions and control. *Biomass Convers. Biorefin.* **2024**, *14*, 27159–27173. [CrossRef]
24. Wan, H.-P.; Chang, Y.-H.; Chien, W.-C.; Lee, H.-T.; Huang, C.C. Emissions during co-firing of RDF-5 with bituminous coal, paper sludge and waste tires in a commercial circulating fluidized bed co-generation boiler. *Fuel* **2008**, *87*, 761–767. [CrossRef]
25. vanKessel, L.B.M.; Arendsen, A.R.J.; de Boer-Meulman, P.D.M.; Brem, G. The effect of air preheating on the combustion of solid fuels on a grate. *Fuel* **2004**, *82*, 1123–1131. [CrossRef]
26. Yang, Y.B.; Ryu, C.; Goodfellow, J.; Nasserzadeh, S.-V.; Swithenbank, J. Modelling Waste Combustion in Grate Furnaces. *Process Saf. Environ. Prot.* **2004**, *82*, 208–222. [CrossRef]
27. Xie, J.; Yang, X.-M.; Zhang, D.T.-L.; Song, W.-L.; Lin, W.-G. Emissions of SO₂, NO and N₂O in a circulating fluidized bed combustor during co-firing coal and biomass. *J. Environ. Sci.* **2007**, *19*, 109–117. [CrossRef] [PubMed]

28. Li, J.; Yang, W.; Blasiak, W.; Ponzio, A. Volumetric combustion of biomass for CO₂ and NO_x reduction in coal-fired boilers. *Fuel* **2012**, *102*, 624–633. [[CrossRef](#)]
29. Kubacki, M.; Ross, A.B.; Jones, J.M.; Williams, A. Small-scale co-utilisation of coal and biomass. *Fuel* **2012**, *101*, 84–89. [[CrossRef](#)]

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