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Drivers of biomass co-firing in U.S. coal-fired power plants



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ABSTRACT

Substantial knowledge has been generated in the U.S. about the resource base for forest- and other residue-derived biomass for bioenergy including co-firing in power plants. However, a lack of understanding regarding power plant-level operations and manager perceptions of drivers of biomass co-firing remains. This study gathered information from U.S. power plant managers to identify drivers behind co-firing, determine key conditions influencing past and current use, and explore future prospects for biomass in co-firing. Most of the biomass used in co-firing was woody biomass procured within 100 km of a power plant. Results show that the most influential co-firing drivers included: adequate biomass supply, competitive cost of biomass compared to fossil fuels, and costs of biomass transport. Environmental regulations were generally considered second-most influential in decisions to test or co-fire with biomass, but were of high importance to managers of plants that are currently not co-firing but may in the future.

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1. Introduction

Combustion of fossil fuels provided about 84% of total energy and about 69% of electricity consumed in the U.S. in 2010 [1]. Coal is the most highly used fuel for electricity production in the U.S.; about 1000 Mt of coal were fired to generate electricity and heat in 2008 [2]. Since the early 1990s, coal has steadily provided about 51% of electricity annually consumed in the U.S. since the early 1990s [3,4].

Although non-renewable fossil fuels dominate the energy sector, energy from a variety of biomass sources provided about 3% of total energy consumption in 2008 and exceeded 4% for the first time in 2009 [5]. Among different bioenergy feedstocks, woody biomass supplied the greatest share of renewable energy – about 53% in 2010 [1]. Woody biomass

was used for energy primarily in the forest products industry (68%), for electric power generation (9%), and for residential (20%) and commercial (3%) heating [5]. Woody biomass used for energy production comes primarily from two sources: residues generated in the manufacture of forest products and fuelwood used in the residential and commercial sectors. Residues from the forest products manufacturing include primary and secondary mill by-products generated in making lumber, veneer and panels, and black liquor generated in the pulping process, among others. Fuelwood is wood that is harvested from forests and used directly for residential and commercial heating, as well as electric power production [5]. Other types of woody biomass such as urban wood residues are available at lower volumes, limited to densely populated areas, and are often already used in

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composting or unavailable because of excessive contamination [5].

Various types of technologies can be used to convert biomass to energy. These include: (1) direct firing or co-firing biomass for electricity, heating and cooling, (2) production of liquid biofuels, and (3) gasification of biomass [6,7]. Co-firing refers to the practice of using biofuels as a supplementary energy feedstock in high-efficiency utility boilers [8,9]. An estimated 86 coal-fired power plants used some biomass as of 2007 [2,10]. Co-firing biomass with coal is a popular option because many coal-fired electric plants can use biomass in existing fuel storage and handling systems with relatively minor modifications [3,11–14].

Past research has assessed the conversion of fuel handling systems and boilers to accommodate co-firing of biomass with coal [12,15]. A number of biomass resource assessments at varying spatial scales have evaluated the feasibility of co-firing across the U.S. [4,16,17]. One limitation of these studies is a lack of understanding of factors that influence managers in deciding whether or not to co-fire. For instance, Aguilar et al. [17] estimated resource availability and the likelihood of co-firing in counties of the U.S. Northern Region using a combination of geo-referenced biomass resource and socio-economic secondary data. However, there is still a need to ask plant managers directly for reasons why power plants in the U.S. have or have not incorporated biomass to be co-fired with coal. A direct survey of power plant managers was deemed necessary to determine drivers behind past decisions and prospects for co-firing in the future.

There were several reasons for investigating coal-fired power plants. First, biomass (most of it woody biomass) is the main source of renewable energy in the U.S. and an important share is used by the electric generation sector. Second, establishment of dedicated plants burning only biomass is rare given economic and logistic challenges, thus, co-firing has emerged as a feasible alternative. Third, co-firing is already occurring in the market with success, yet the literature discussing factors driving the decision process at the power plant-level is scarce [18]. Fourth, biomass use has been reported to be influenced by local (power plant-level) perceptions of feasibility and interest, not solely on alternative energy prices or output from other industries [19].

2. Aim and objectives

The aim of this study was to identify salient drivers behind consideration, testing, and implementation of biomass co-firing operations in U.S. power plants. Specific objectives included to: (1) identify factors influencing biomass co-firing in U.S. power plants, (2) determine the drivers behind decisions to co-fire, (3) determine principal drivers behind current and past co-firing testing and implementation, and (4) identify factors most likely to influence future decisions to use biomass in co-firing.

3. Theoretical framework

Identification of drivers that influence past, current and future co-firing was framed within industrial regional science.

Regional science suggests that industries, such as power generation, tend to locate in areas according to internal, external, and location-specific drivers. Internal drivers include firm-specific conditions such as a particular production technology, management, ownership structure, growth rate, employment and profits, among others. External factors include government policy and regulations, regional economic structure, and technological progress. Location-specific factors refer to absolute and relative characteristics of the location such as access to input materials, distance to customers and suppliers, and the presence of support services [16]. This framework is similar to the triangular model of clean technology adoption that suggests decisions to adopt environmentally-friendly technologies are a function of the interaction between external actors and factors, firm internal factors and characteristics of the technology [20].

Internal, external and location-specific drivers influence decisions to adopt new practices, such as use of biomass for co-firing with coal. One of the most important internal drivers is operational and maintenance costs of co-firing equipment. The significance of this driver greatly depends upon the current fuel delivery system and boilers used by a particular plant. Stoker, cyclone, and fluidized bed boilers are the most adaptable to co-firing due since they can burn coarser fuels and fuels with higher moisture content [3,12]. Other internal drivers include voluntary commitments to renewable energy standards and availability of internal corporate capital investments for conversion to co-firing. Regulatory drivers are major external drivers and include state and federal regulations regarding biomass procurement and use, carbon dioxide emissions and other greenhouse gases, and criteria pollutants, as well regulations concerning implementation of state-level renewable energy portfolio standards [17]. Additional external drivers include state or federal subsidies and availability of capital for investment. Location-specific factors are characteristics of the area surrounding individual power plants. Three of the most important location-specific drivers are the cost of biomass compared to coal, adequate year-round biomass supply, and cost of biomass transport [21,22]. The technical feasibility of co-firing biomass is highly dependent upon efficient transport of biomass from the source to the power plant [12,16,23].

4. Methods

A questionnaire was developed and reviewed by researchers and practitioners at the University of Missouri and the U.S. Forest Products Laboratory and pre-tested among a group of 10 power plant managers in July–October 2011. The survey instrument consisted of four sections to gather information about (1) power plant descriptors, (2) key factors that influence the decision to co-fire across power plants, (3) drivers for power plants that have co-fired or tested with biomass, and (4) drivers for power plants that have not tested or co-fired but may either begin or consider doing so in the future. To distinguish between factors that affected decisions to test/stop testing or co-fire in the past and those that may influence a decision to begin co-firing in the future we asked respondents to identify their power plants in one of three categories. These reflected whether a power plant has tested co-firing in the past, is

currently or has adopted co-firing, or has never tested or implemented co-firing. Within the general categories that have tested/co-fired we added a second level of distinction to identify plants currently testing/co-firing and those that have stopped. Hence, we had six power plant categories: (1) currently testing, (2) stopped testing, (3) currently co-firing, (4) stopped co-firing, (5) never tested/co-fired but may co-fire in the future, (6) never tested/co-fired and no future plans for co-firing.

4.1. Power plant descriptors

Information was collected from all power plants on generation capacity, boiler technology, and coal transport distance. We asked whether the power plant was an electrical facility or a cogeneration (electricity and thermal) facility. Respondents were asked to provide plant generation capacity and annual net power generation. Managers that indicated cogeneration status were asked to indicate the per-hour steam production of their plant. We asked all respondents to indicate the number of boilers used by boiler type. Possible boilers types included pulverized coal, stoker, or fluidized bed. Managers were asked to indicate average coal transport distance and whether or not (to their knowledge) there is a pulp mill, paper mill, or saw mill within 80 km of their power plant. All managers participating in this study were asked to indicate the co-firing status of their plant.

Descriptor information from power plants that have tested with biomass included specific testing operations, equipment modifications, dominant biomass feedstocks used, biomass feedstock transport, and cost of biomass feedstocks. We asked power plant managers if they had conducted supply and transport testing or feeding system/boiler system testing. We also asked the managers to indicate which types of biomass were used for testing of co-firing (by percentage of weight). Possible answers were forest biomass, wood manufacturing residues, herbaceous, corn stover, miscellaneous residues, landfill gas, and other. Information gathered from power plants that have or are currently co-firing with biomass included specific testing operations, equipment modifications, dominant biomass feedstocks utilized, biomass feedstock transport, and cost of biomass feedstocks. We asked whether or not their power plant had required modification or replacement of fuel systems or boilers to facilitate co-firing. We then asked which types of biomass were used for co-firing (by percentage of energy output). As was the case of testing, possible answers included forest biomass, wood manufacturing residues, herbaceous, corn stover, miscellaneous residues, landfill gas, and other. We also asked for the average price of biomass used as a percentage (greater than or less than) the price of coal. Information gathered from power plants that have never co-fired or tested with biomass included specific resource analyses, technical modifications, and localized support and infrastructure. Among these, we asked whether or not they had conducted a biomass resource analysis.

4.2. Identification of key factors influencing decisions for biomass co-firing

Based on our theoretical framework, a list of drivers capturing internal, external and location-specific factors was generated

(Table 1). All respondents were asked to indicate the importance, based on their knowledge and experience, of each variable on the decision of a power plant to incorporate co-firing. Importance was measured on a 5-point scale with 1 = “not important at all”, 3 = “somewhat important”, and 5 = “very important”.

Exploratory factor analysis was used to reduce the number of variables presented and identify latent factors. Under the concept of factor analysis, the factors should be as distinct as possible from all other underlying factors in the solution [24,25]. This was an exploratory factor analysis in that we did not assume any known common factors going in to the analysis, but rather used it as a tool to determine common factor characteristics and reveal the apparent logic behind the inclusion of certain drivers within each factor. One point of interest was to compare latent drivers identified through factor analysis and the theoretical internal, external, and location-specific factors described previously. The analysis used a principal component extraction followed by a Varimax orthogonal rotation. Criterion for associating variables to a latent factor was based on a minimum loading of 0.40 [26].

4.3. Determination of drivers behind current and past co-firing testing and implementation

To elucidate the effects of each driver on a particular power plant, instead of a general statement as described above, each

Table 1 – Constructs included as proxies for co-firing drivers, including the theoretical factor designation of internal, external, or location-specific.

The decision to test/stop testing, co-fire/stop co-firing, begin/consider testing or co-firing in the future In your power plant was/would be influenced by ^a :	Theoretical factor
Voluntary corporate commitments to renewable energy standards	Internal
Corporate capital investments	Internal
Operation and/or maintenance costs of co-firing	Internal
State or federal subsidies for renewable energy production	External
Availability of external capital investments	External
Low interest loan guarantees from external sources	External
Environmental regulations regarding biomass procurement and usage	External
Renewable portfolio standards	External
Environmental regulation regarding criteria pollutants	External
Environmental regulations regarding greenhouse gases	External
Likelihood of end users' willingness-to-pay a price premium	External
Cost of biomass compared to fossil fuels	Location-specific
Cost of biomass transport	Location-specific
Adequate biomass supply	Location-specific

^a Responses measured on 5-point Likert scale (1 = “not important at all”, 3 = “somewhat important”, and 5 = “very important”).

manager was asked to rate the list of constructs presented in Table 1 in response to customized statements. Managers of plants that have tested or are currently testing co-firing were asked to rate each statement using a 1–5 Likert scale (1 = Strongly disagree, 3 = Neither agree nor disagree, 5 = Strongly agree) in response to this statement: “The decision to test with biomass in your power plant was influenced by ...”. Managers that have tested with biomass but have stopped as of 2012 were asked to rate the same constructs but in response to the statement: “The decision to stop testing with biomass in your power plant was influenced by ...”. Managers that have co-fired or are currently co-firing with biomass were asked to react to the statement: “The decision to co-fire in your power plant was influenced by ...”. Managers that have co-fired with biomass but have stopped as of 2012 were asked to rate the constructs in response to the statement: “The decision to stop co-firing in your power plant was influenced by ...”. Finally, Managers that never tested or co-fired recorded ratings in response to the statement: “A decision for your power plant to begin biomass co-firing operations in the future would be influenced by ...”; and Managers that have no future plans of co-firing rated constructs in response to the statement: “A decision for your power plant to consider co-firing operations in the future would be influenced by ...”. Note that respondents who have stopped testing with biomass were included in the group that has tested with biomass in the past. Therefore, responses to both statements were not statistically independent. Likewise, managers who stopped co-firing were included in the group that co-fired with biomass in the past.

Student's *t*-statistics tested the hypothesis that the mean response for each driver was significantly different from the neutral response of 3. Unlike the analyses for testing and co-firing operations, the two status designations (plants that may co-fire in the future and plants that have no future plans for co-firing) were statistically independent from one another due to separate categorization. Therefore, we used Student's *t*-statistics to test the hypothesis that the mean response for each driver was significantly different between managers that may co-fire in the future and those that have no future plans for co-firing.

4.4. Sample and data collection

The population of interest consisted of all 630 U.S. power plants with capacity ≥ 5 MW and using coal as either a primary or secondary fuel for either electricity or heat generation as listed on ‘UDI Who's Who at Electric Power Plants’ [27]. This was the most comprehensive and up-to-date directory of power plants in the U.S. at the time of the study. Given that we targeted the universe of U.S. power plants within our capacity and feedstock definition, this study started as a census with respondents constituting a sample of this population.

Data was gathered using a hybrid online/mail-based survey of power plant managers in the U.S. following the Tailored-design methods [28]. In early November 2011, a link to the online survey was mailed to power plant managers followed by a reminder postcard two weeks later. This initial mailing (first waive) was followed up by two mailings of paper versions of the survey (second waive) that could have been

completed and returned using a pre-paid envelope. No monetary incentive was used in this survey to avoid any potential bias in responses. The survey protocol met approval from the University of Missouri Institutional Review Board. Non-response bias was evaluated by using Student's *t*-statistics to test the difference between the sample means of plant capacity and annual net generation for the respondents and all other coal-fired power plants in the U.S. as listed by the EPA [10]. Additionally, we compared mean responses for co-firing drivers from the initial mailing to those returned in the second waive [29]. We used Student's *t*-statistics to test the difference between early and late respondents mean values for plant capacity, annual net generation, and importance of drivers listed in Table 1.

5. Results and discussion

We received 68 responses through the online version and paper versions of the survey for an adjusted response rate of 11% after removing undeliverables and companies reported to be out of business. Although the small response rate in this survey suggests this study would be exploratory, our sample effectively corresponds to 11% of the population of U.S. power plants that accounted for about 8% of electricity generated by coal-fired power plants as of 2007 [10]. Of all respondents, 60% of power plant managers worked at electrical facilities while 40% worked at cogeneration (electricity and thermal) facilities. Power plant type served as an indicator for plants that may have an annual electricity generation disproportionate to the annual fuel input for the power plant. Also, co-generation facilities can often represent cases in which the power plant is located closer to population centers than many electricity plants due to the delivery system of thermal energy to end users. Non-response bias was found to not be statistically significant at $\alpha = 0.01$ for all variables assessed. Suggesting that the sample obtained through the survey adequately represents the U.S. population of coal-fired power plants. Respondents represented power plants located in all four DOE regions – West, Midwest, Northeast, and South.

5.1. Power plant descriptors

Generation capacity and net generation of plants in the sample varied greatly between plants with different co-firing status (Table 2). Power plants that have/are co-firing reported the lowest values for capacity and generation. This is most likely due to logistics requirements of co-firing. Larger power plants tend to be located in or near highly populated areas where

Table 2 – Median values for generation capacity, annual net generation of electricity, and steam production aggregated by plants that have tested, plants that have co-fired, and plants that have done neither.

	Tested	Co-fired	Neither
Generation capacity (MW)	63	55	235
Annual net generation (GWh)	775	237.5	1040
Steam production (Mg h^{-1})	340.2	260.8	310.05

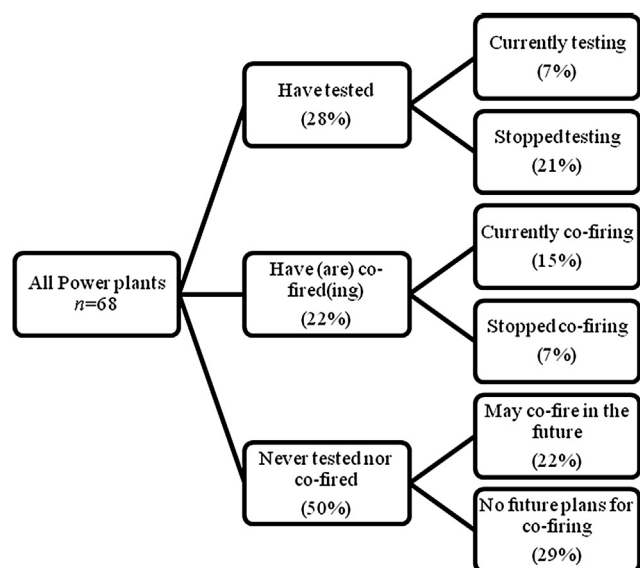


Fig. 1 – Breakdown of respondents to survey of power plants identifying coal-fired power plant management that have tested, are currently co-firing or have not utilized or tested biomass in co-firing.

accessibility to biomass feedstocks is more challenging resulting in higher transport and fuel storage costs.

Variables that showed a high importance in influencing the decision to co-fire include boiler type, coal transport method and average distance, and proximity of biomass resources. The highest percentage of respondents (65%) indicated that their power plant utilizes pulverized coal boilers with an average of three boilers per plant. However, the percentages of plants using stoker boilers and fluidized bed boilers were sizeable at 50% and 43% respectively. The high percentage of plants using stoker boilers and fluidized bed boilers indicates that many of them could convert at least some of their boilers for co-firing without having to grind biomass to smaller sizes as is needed for pulverized coal boilers.

Sixty-one percent indicated coal transport distances greater than 480 km and 59% indicated that their plants used railways to transport coal. Forty-one percent did not know if there was a biomass source within 80 km of their power plant. Thirty-seven percent indicated that there was at least one saw mill within 80 km of their power plant, whereas 12% and 10% of respondents indicated a presence of paper mills and pulp mills, respectively. These results show that many plants (if they are not already using biomass) may obtain wood processing residues with relatively short transport distances.

Descriptors specific to biomass testing or co-firing were obtained separately for respondents by testing or co-firing status. Fig. 1 shows the breakdown of respondents by biomass testing and co-firing status.

5.1.1. Descriptors for power plants that have or are currently testing with biomass

Of the managers of power plants where biomass has been tested, 56% reported that their plant had conducted supply and transport testing while 74% said that their plant had

conducted feeding system/boiler testing. The level of agreement for contribution to the success of both types of testing was highest for technical feasibility (3.7–3.9) and environmental standards (3.6–3.7), which were both significantly different from the neutral value of 3 (p -value < 0.05). The level of agreement to financial viability contributing to the success of testing was much lower (2.1–2.2), also significantly different from 3 (p -value < 0.05) indicating that most challenging issues to system conversion and operation of co-firing were still economic in nature.

The highest average percentage of all biomass used for testing by all respondents (by total annual fuel weight) was for wood manufacturing residues that had been converted into pellets (20%), while the second highest percentage was pelleted corn stover (14%). This was not surprising as these two types of biomass are relatively abundant across the U.S. However, the findings for transport distance were unexpected. Of the managers that have tested or are testing with biomass, 28% indicated average biomass transport distances of 65–100 km. An equal percentage of respondents (28%) indicated an average transport distance of >160 km. A little more than half of plants had either short transport distances or very long transport distances, in contrast to average transport distances for currently co-firing plants as discussed next. This is most likely an indication that many plants have focused biomass testing efforts on internal operations (boilers and fuel systems) and not testing use of local supply infrastructure. Conversely, high transport distance was most likely correlated with a low level of agreement for financial viability.

5.1.2. Descriptors for plants that have or are currently co-firing with biomass

Of managers that have co-fired with biomass, 64% said that their plant required fuel system modification while only 21% said that their plant required boiler modification. Most of the plants that have co-fired use boilers that can be easily adapted to burn some quantity of biomass, coinciding well with the fact that 50% of respondents indicated use of stoker boilers, which require little modification for biomass [30–32]. The fact that 64% of the plants required fuel system modification is logical, as most existing fuel systems are designed for coal delivery and different particles sizes, moisture content, and biomass characteristics can cause problems if there is no modification.

Woody materials comprised 51% of biomass of all materials used for co-firing (by annual energy output). The highest average percentage (39%) of biomass was in the form of chipped/ground forest biomass, while the second highest percentage (12%) was pelletized wood manufacturing residues. This differs from biomass testing, where the greatest share was from pelletized wood manufacturing residues. Unlike plants that are testing, an operational co-firing operation requires a reliable biomass supply, and it may not be possible relying only on manufacturing residues as most wood mill residues are already being used for other applications (e.g. mulch, power for the wood mill, pulping liquors) [17,33].

Almost 70% of plants that have co-fired indicated an average transport distance of less than 100 km. This seems logical, as transport distances in excess of 80–100 km will often increase the cost of biomass supply beyond that of

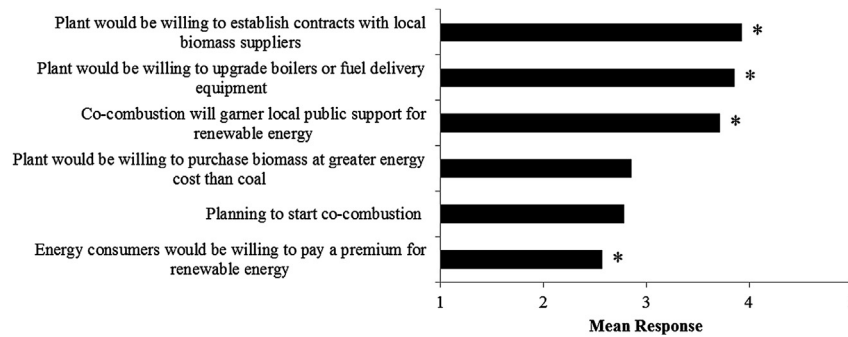


Fig. 2 – Mean Likert-scale values (1 = Strongly disagree, 3 = Neither agree nor disagree, 5 = Strongly agree) to statements concerning technical modifications, costs, local opinions, and future plans provided by managers of power plants that have never tested or co-fired with biomass. The symbol “*” indicates statements for which the mean response was significantly different than 3 (p -value < 0.05).

coal [4,16]. One anticipated difference between plants that have only tested with biomass and plants that have actively co-fired was their direct knowledge of the difference in cost between biomass and coal. The variation in transport distance for plants testing with biomass is an indication that such plants were initially less concerned with the cost of biomass than testing technical feasibility of co-firing. The highest percentage of managers that have co-fired (43%) indicated that biomass was, on average, at least 20% less expensive than coal. This is interesting since for most areas of the country, supply and transport infrastructure for coal is better established than for biomass. However, the cost differential is consistent with the reported short biomass transport distances for most power plants, as well as the local network of biomass suppliers that most of these plants have probably established.

5.1.3. Descriptors for plants that have never tested or co-fired with biomass

Of the responses for plants that have never tested or co-fired with biomass, 45% stated that they may consider testing or co-firing in the future, while 55% stated that they had no future plans for co-firing. Forty-three percent of respondents with no future plans for co-firing indicated they had conducted a biomass resource analysis. Fig. 2 shows the mean response to the statements concerning technical modifications, costs, local opinions, and future plans.

The only mean responses that were not significantly different from the neutral value of 3 (p -value > 0.05) pertained to future plans to start co-firing and willingness to use fuel costing more than coal. Managers generally agreed that the local public would support the idea of renewable energy, but there is general disagreement that energy consumers would be willing to pay a price premium for renewable energy. Similarly, most managers would be willing to establish contracts with local suppliers and upgrade equipment for co-firing, but are less agreeable (or neutral) about using a fuel that costs more than coal. This points to the fact that most power plants that have co-fired were using biomass that was at least 20% less expensive than coal, identifying cost difference as a weighty factor for feasibility of co-firing.

5.2. Identification of key factors influencing decisions for biomass co-firing

The exploratory factor analysis yielded five common factors based on maximum likelihood selection and Varimax rotation. A Chi-squared test indicated that more factors were not needed to describe the correlation between the variables (p -value = 0.065). Table 3 shows the variables included in each common factor with corresponding loadings.

Factor 1 was labeled ‘Biomass Supply and Operational Costs’. It included high factor loadings (>0.40) for biomass supply, biomass transport cost, and operational cost. This shows that indicators of biomass supply, as well as transport and operational costs are highly correlated with each other in perceived importance for co-firing operations. Factor 2 was labeled ‘Investments and Loans’. It included high factor loadings for capital investments and loans. Factor 3 was labeled ‘Environmental Policy’ since it includes high factor loadings for all three variables pertaining to environmental regulations and renewable portfolio standards. Factor 4 was labeled ‘End-user Preference’ since it included high factor loadings for variables pertaining to local community and end users of electricity. The final factor (Factor 5) was labeled ‘Corporate Commitments’. It included high factor loading for the variable pertaining to voluntary corporate commitments to renewable energy.

The key factors identified do not align directly with the internal, external, and location-specific factors proposed in the theoretical framework of the study. A result that stands out is that factors 1–3 – the most influential ones – depend heavily on production economics, logistics, and policy considerations.

5.3. Major drivers of current and past co-firing testing and implementation

5.3.1. Testing operations

Fig. 3 shows the mean response of the managers of power plants that have tested and those that have stopped testing for each of the 14 co-firing drivers. In both cases, drivers pertaining to supply costs and operational costs had the highest reported values (Fig. 3), although none of the mean

Table 3 – Factor loadings for five identified common factors, based on levels of importance (1 = not important, 5 = very important) reported by power plant managers.

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
	Biomass supply and operational cost	Investments and loans	Environmental policy	End-user preference	Corporate commitments
Biomass transport cost	0.73	0.14	0.09	−0.04	0.15
Operation and/or maintenance costs of co-firing	0.71	−0.06	−0.01	0.14	0.02
Adequate biomass supply	0.49	0.02	0.10	0.12	0.003
Environmental regulations for biomass procurement and usage	0.40	0.08	0.64	0.02	−0.22
Internal (corporate) capital investments	0.37	0.08	−0.34	0.06	0.02
Local communities acceptance of renewable energy	0.36	−0.19	−0.004	0.57	0.07
Cost of biomass compared to fossil fuels	0.33	−0.01	−0.01	0.28	−0.10
Low interest loan guarantees from external sources	0.14	0.99	0.06	0.003	−0.01
External (outside capital investments	0.14	0.69	0.003	−0.06	0.07
Voluntary corporate commitments to renewable energy	0.09	0.05	0.13	0.06	0.98
Likelihood of end user's willingness-to-pay a price premium	0.05	0.21	−0.04	0.92	0.05
Environmental regulations for greenhouse gases	0.04	0.15	0.67	−0.04	0.04
Renewable portfolio standards	−0.03	0.03	0.61	0.01	0.24
State or federal subsidies	−0.14	0.34	0.13	0.11	−0.01

responses for these drivers was significantly different from the neutral value of 3 (p -value > 0.05). However, drivers such as end users' willingness-to-pay price premiums and corporate capital investments were deemed important when compared to drivers such as environmental regulations. The cost of biomass compared to fossil fuels, and operation costs both had a higher effect on the decision to stop testing than the decision to begin testing. This could be due to increased awareness of the magnitude of these costs gained during biomass testing. Recall that Factor 1 (Biomass Supply and Operational Costs) was identified as being an important factor that would persist throughout the assessments of testing and co-firing. As shown in Fig. 3, the drivers that were most

important in both the decision to start testing and the decision to stop testing all belong to Factor 1 or Factor 2. This indicates some of the most crucial factors for testing are a combination of (mostly localized) operational, infrastructural, social, and economic considerations [17,34,35]. These results are similar to findings by del Río González [20] concerning adoption of technologies for pulp and paper manufacturing firms, which indicated personal commitments and cost savings as key drivers in the decision to adopt new technologies. Environmental regulations and capital investments (both internal and external) were generally considered to be of lower importance to testing operations.

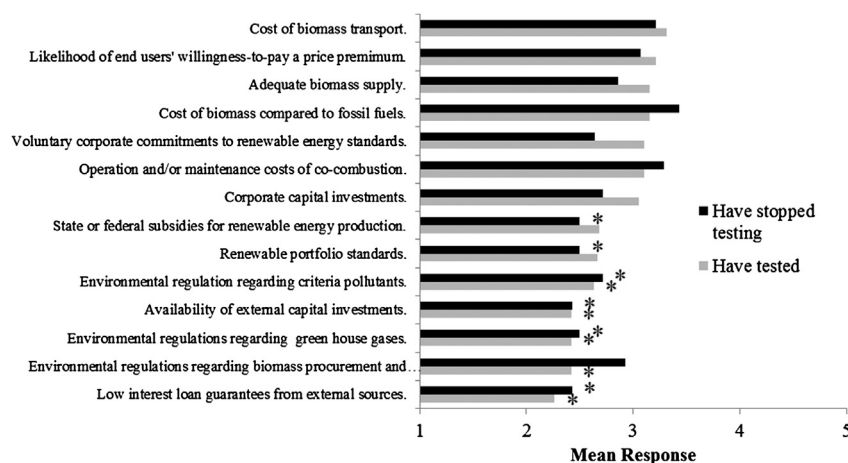


Fig. 3 – Mean Likert-scale values (1 = Strongly disagree, 3 = Neither agree nor disagree, 5 = Strongly agree) to statements concerning drivers influencing the decision to test with biomass and the decision to stop testing. The symbol “*” indicates statements for which the mean response was significantly different than 3 (p -value < 0.05).

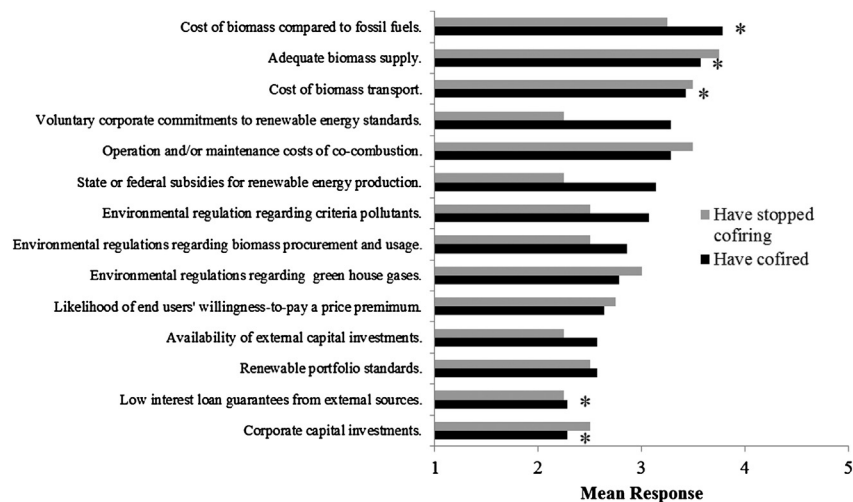


Fig. 4 – Mean Likert-scale values (1 = Strongly disagree, 3 = Neither agree nor disagree, 5 = Strongly agree) to statements concerning drivers influencing the decision to co-fire and the decision to stop co-firing. The symbol “*” indicates statements for which the mean response was significantly different than 3 (p -value < 0.05).

5.3.2. Currently co-firing operations

Fig. 4 shows the mean response of managers that have co-fired and managers that have stopped co-firing for each of the 14 drivers described in Table 1. As with testing operations, the drivers with the greatest effect on the decision to co-fire were cost of biomass compared to fossil fuels, adequate biomass supply, cost of transport, and operational costs of co-firing. The mean responses were significantly different from the neutral response of 3 (p -value < 0.05) for plants that have co-fired but not for plants that have stopped co-firing. Although cost of biomass compared to fossil fuels is most influential for the decision to co-fire, it was considerably less influential in the decision to stop co-firing. Biomass supply, operational costs, and adequate biomass supply were more influential in the decision to stop co-firing. This could indicate that the main challenges to continuous co-firing have more to do with the sustainable resource supply and technical feasibility than the difference in cost between biomass and coal. Overall, the decision to stop co-firing seemed highly correlated with supply and operational costs, whereas environmental regulations were much less important. These results coincide with past studies identifying localized biomass supply as a limiting factor for co-firing operations [8,35,36].

5.3.3. Future prospects

Fig. 5 compares the mean responses between managers that may co-fire in the future and managers that have no plans to co-fire for the 14 drivers in Table 1. As with testing operations and co-firing operations, some of the most important drivers influencing future consideration of co-firing pertain to biomass supply, biomass cost compared to coal, and operational costs. Mean responses for all of these drivers were significantly different from the neutral response of 3 (p -value < 0.05). Environmental regulations were much more important for respondents that are or may consider co-firing in the future than for respondents who have already tested or co-fired. This indicates that public policy stimuli can lead

power plants to consider co-firing. The finding of the importance of environmental regulations is similar to findings by del Río González [20] which identified regulatory restrictions as a key driver in the decision to adopt new technologies. Plants that are already considering co-firing reported environmental regulations for both greenhouse gases and criteria pollutants to be influential in the decision making process. Plants not considering co-firing deemed environmental regulations to have a notable but somewhat lower influence and consider biomass supply and costs to be more important. Those with no plans to co-fire also consider availability of external capital, loan guarantees, and corporate commitment to be more important than respondents that may co-fire. This indicates that plants not considering co-firing are nearly as concerned with availability of capital, corporate commitments, and additional funding for conversion as they are with environmental regulations.

6. Conclusions

We identified four latent factors to influence biomass co-firing in U.S. power plants: (1) biomass supply and operational costs, (2) investments and loans, (3) environmental policy, (4) end-user preference, and (5) corporate commitments. Reported drivers behind the decision to test or engage in longer term co-firing pertained to biomass source and transport distance. Adequate supply combined with a limited transport distance and associated biomass cost competitiveness with fossil fuels are critical to long-term co-firing. One of the most important factors that will influence feasibility of co-firing is the establishment of local partnerships for the supply of biomass and supportive transportation infrastructure. The main energy feedstock use in commercial co-firing was woody biomass, mainly in the form of non-pelletized materials. Woody biomass comprised 51% of all biomass used for co-firing. Environmental regulations, in addition to biomass supply and transport costs,

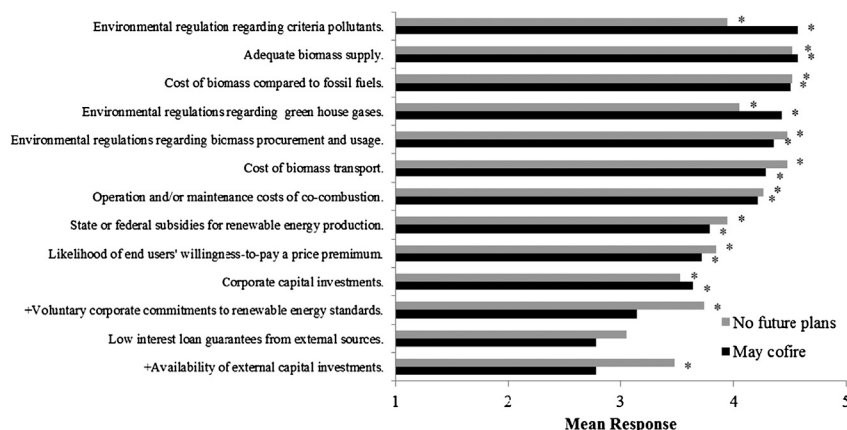


Fig. 5 – Mean Likert-scale values (1 = Strongly disagree, 3 = Neither agree nor disagree, 5 = Strongly agree) to statements concerning drivers influencing the decision to co-fire in the future and to consider co-firing in the future. The symbol “*” indicates mean response was significantly different than 3 (p -value < 0.05). The symbol “+” indicates statements for which the mean response between respondents who may co-fire in the future and respondents who have no future plans for co-firing was statistically different (p -value < 0.05).

will likely be the main factors considered by power plants to co-fire with biomass in the future.

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