International Journal of Food and Agricultural Economics
ISSN 2147-8988, E-ISSN: 2149-3766
Vol. 3 No. 3, Issue, 2015, pp. 15-30

BENEFIT COST FOR BIOMASS CO-FIRING IN ELECTRICITY GENERATION: CASE OF UTAH, U.S.

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Abstract

Policy making regarding biomass co-firing is difficult. The article provides a benefit-cost analysis for decision makers to facilitate policy making process to implement efficient biomass co-firing policy. The additional cost is the sum of cost of the biomass procurement and biomass transportation. Co-benefits are sales of greenhouse gas emission credits and health benefit from reducing harmful air pollutants, especially particulate matter. The benefit-cost analysis is constructed for semi-arid U.S. region, Utah, where biomass supply is limited. Results show that biomass co-firing is not economically feasible in Utah but would be feasible when co-benefits are considered. Benefit-cost ratio is critically dependent upon biomass and carbon credit prices. The procedure to build the benefit-cost ratio can be applied for any region with other scenarios suggested in this study.
Key Words: *Biomass co-firing; benefit cost analysis; carbon credit; co-benefit; electricity*

1. Introduction

Climate change regulations and governmental policies regarding coal-fired power plants in the U.S. have strengthened a demand for environmentally benign renewable energies such as wind, solar, geothermal and bioenergy. Among them biomass co-firing, use of biomass to generate electricity in the same boiler, has attracted researchers' and decision makers' attentions. The three primary types of biomass used for co-firing are agricultural residues, forest residues, and herbaceous energy crops (National Energy Technology Laboratory, 2012). Usually biomass is more expensive than coal and thus public policies are important to increase the use of biomass and make biomass feedstock economically competitive (Oliveira, 2002). Unfortunately, however, policy making in environmental regulation, such as biomass co-firing, is usually difficult (Bromley, 2009).

A benefit cost analysis is one of techniques to provide policy makers and interest groups with the information needed to implement efficient biomass co-firing policy (Tietenberg, 2009). Identifying the costs and benefits is a valuable part of the policy process (Tietenberg, 2009). The benefit-cost analysis is useful and has played an important role in regulatory policy on improving the environment (Arrow et al., 1996). This study is motivated by providing a benefit-cost results to facilitate policy making process. More specifically this study attempts to identify benefit-cost ratio of the biomass co-firing considering additional costs, greenhouse gas emission reduction and health benefits from the biomass co-firing. The state of Utah in the U.S. is selected to demonstrate how to construct the benefit-cost look-up table. Secondary objective of the study is to investigate physical and economic feasibility of the biomass co-firing in semi-arid regions (thus it is not agricultural production region) in the U.S. such as the state of Utah which is located west of the U.S. (Figure 1)

Figure 1. Location of Utah and Coal-fired Power Plants (Gray dots)

In Utah, 81% of net electricity generation comes from coal (15% from natural gas) in 2013 according to the US Energy Information Administration, which is much higher than the US average (39% from coal in 2013). Utah has established the voluntary Renewable Portfolio Standards (RPS) to aim to produce 20% of electric sales from renewable sources other than hydro power by year 2025 (US Energy Information Administration, 2012b). Farming, mostly hay and corn to support livestock production, plays an important role in rural Utah even though Utah is not a major agricultural production region in the U.S.[1] Policy makers in Utah (and surrounding regions) want to know the physical and economic feasibility of the biomass co-firing and its potential in the region (Western Governors' Association, 2006). Note that, in this article, only crop residues will be considered as biomass feedstock. This is because the use of energy crops for electricity generation is yet to be practiced in Utah and it is hard to find the county level data on forest resources and the landfill biomass. In addition forests are far away from power plants which make forest residue unattractive.

Section 2 discusses the biomass co-firing in Utah in general and identifies additional costs adopting the biomass co-firing in electricity generation. Section 3 discusses the potential benefits from the biomass co-firing including greenhouse gas (GHG) emission reduction and harmful air pollutants, particulate matter (PM), emission reduction. Section 4 describes how to generate the benefit-cost look-up table and section 5 concludes the study.

2. Biomass Co-Firing, Biomass Supply in Utah, and Additional Costs

First research question is to examine if Utah can supply enough crop residues for the biomass co-firing. Crop production and crop residue availability are calculated to determine

[1] The climate in Utah is semi-arid or steppe where precipitation is below potential evapotranspiration but not extremely. Utah receives 305 mm – 380 mm precipitation annually.

the biomass potentiality to meet the demand of coal-fired power plants at various co-firing rates. The biomass co-firing in this article refers to combustion of biomass along with coal in a power plant to generate electricity which has been seen as the technology for electric power generation in U.S. Since it uses the existing coal fired power plant it is cost effective as well as this technology has also benefited the environment by mitigating CO_2 emissions and reducing air pollutants (Battista, Hughes & Tillman, 2000). Transportation model is employed to determine the transportation cost of biomass for co-firing in coal-fired power plants. It identifies the optimal biomass supply locations with minimal transportation cost. Also, a levelized electricity generation cost is computed to assess the cost competitiveness of crop residue co-firing with coal for electric power generation in Utah.

2.1. Physical Feasibility of Biomass Feedstock

2.1.1. Harvestable Crop Residues

Although Utah is the second driest state of the U.S. there are some niches of biomass production. Harvestable crop residue in county i, s_i, is calculated as follows:

$$s_i = \sum_k 0.6 \cdot prod_{ik} \cdot \frac{HHV_k}{HHV_{wheat}} \qquad (1)$$

where s_i is the harvestable crop residues in county i in wheat-straw tonne, $prod_{ik}$ is the crop k={barley, corn, oats, wheat} production in county i from 2007 Agricultural Census (http://www.agcensus.usda.gov/), and HHV_k is the higher heating value for residue k from ECN Phyllis database (https://www.ecn.nl/phyllis2/). The HHV ratio of crop k and wheat allows us to convert crop k to wheat-straw tonne. For example, one tonne of corn stover is equivalent to 1.11 tonnes of wheat straw. The number, 0.6, in equation (1) is the crop residue removal rate which means that 60% of crop residue can be safely removed from the fields (without disturbing cropland), which is come from Lindstrom et al. (1981) and Hettenhaus, Wooley & Wiselogel (2000). Neighboring counties in Idaho are included as the potential supply of biomass supply regions because Utah doesn't produce enough biomass feedstock for all the coal-fired power plants in the state.

2.1.2. Transportation Model

A transportation model identifies the biomass supply regions that minimize the transportation cost for transporting biomass to different power plants. The model is given by:

$$\min_{x_{ij}} \quad p\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} c_{ij}x_{ij} \qquad (2)$$

$$s.t. \quad \sum_{j=1}^{J} x_{ij} \le s_i \;\; for\ all\ i, \quad \sum_{i=1}^{I} x_{ij} \ge d_j \;\; for\ all\ j\ and\ \ x_{ij} \ge 0 \quad for\ all\ i,j$$

where, i stands for (possible) biomass production regions (counties), j is the index of (coal-fired) power plants, x_{ij} represents the amount of biomass transported from i to j, c_{ij} represents the unit transportation cost from i to j, s_i is the biomass supply available in the region i identified using equation (1), and d_j stands for the biomass demand from the power plant j. Note that d_j is dependent upon the exogenously determined biomass co-firing rates, for example, 5%, 10%, and 15%. p in the objective function stands for the price of biomass and thus the objective function in equation (2) is the total cost of the biomass co-firing, i.e. the sum of cost of biomass procurement and transportation.

Transportation cost, c_{ij}, is the cost required to transport crop residue from the supply regions to the power plants. One of the key elements of transportation cost is the distance between supply regions and power plants.[2] The second part of the transportation cost is a hauling cost. To calculate the hauling cost per ton of biomass, a formula in equation (3) is utilized which was derived by (McCarl et al., 2000):

$$hc_{ij} = \frac{2cpm \cdot dst_{ij} + fx}{sz}, \tag{3}$$

where hc_{ij} is the hauling cost between a supply region i and a power plant j, cpm represents the (unit) cost per mile, dst_{ij} is the distance between i and j, fx stands for a fixed cost for loading and unloading, and sz is a loading size.[3]

2.1.3. Biomass Requirements by Power Plants

Annual biomass requirement for the 100-MW power plant at 5% co-firing rate requires 350 billion BTU because 100-MW power plant's annual energy requirement is 7 trillion BTUs [11]. A 100-MW power plant needs 22,208 tonnes of wheat residue based on the wheat-straw HHV. Currently eight coal-fired power plants are on operation in Utah. This study estimates the quantity of biomass residue required for different co-firing rates, 5% and 10% (Table 1).

Table 1. Biomass Requirement by Power Plants

Power Plants	5% co-firing (wheat-straw tonnes)	10% co-firing (wheat-straw tonnes)	Power plants Capacity (MW)	Electricity Production (MWh)[a]
Bonanza	95,946	191,891	500	3,384,000
Carbon	36,267	72,534	189	1,279,152
Deseret	8,251	16,503	43	291,024
Hunter	282,464	564,927	1,472	9,962,496
Huntington	191,123	382,235	996	6,740,928
Intermountain	314,701	629,402	1,640	11,099,520
Smelter	34,924	69,848	182	1,231,776
Sunnyside	11,149	22,298	58	393,220.8

Note: [a] Assuming net operation days are 282; Electricity production = day × capacity × 24 (hours)

[2] Transportation distance was calculated using the Google map assuming the biomass is transported using the highways and major roads. County seat is used as the reference for the transportation of crop residues from the supply regions. Eight existing coal-fired power plants are identified which are scattered around Utah.

[3] Hauling cost parameters are given by: cpm = \$2.2/mile, fx = \$90, and sz = 20 tons, respectively based on (Sokhansanj, Kumar, and Turhollow, 2006)

2.1.4. Results of Transportation Model

The transportation model in equation (2) is run with the harvestable crop residues, annual biomass requirements, and the unit transportation cost. The transportation model suggests that crop residues in Utah can only support a few power plants near supply regions, Carbon, Deseret, Smelter and Sunnyside power plants. Hunter and Huntington power plants do not have biomass supply (less than 1% of total biomass requirements). Bonanza power plant is supplied 11% of feedstock requirement and Intermountain power plant is supplied only 30% of feedstock requirement. Thus, to make biomass co-firing feasible for all power plants in Utah, it is essential to transport biomass from other regions outside of Utah.

As Idaho doesn't have a large coal-fired power plant, neighboring Idaho counties can be potential biomass supply regions. Thirteen Southern Idaho counties are included in the model where plenty of crop residues are available. Other neighboring counties in Nevada, Arizona, Colorado, and Wyoming are not considered because they do not produce enough biomass (Nevada and Wyoming) or the coal-fired power plants exists (Arizona and Colorado). Using the similar processes and assumptions, crop residues available from Idaho are calculated. Transportation costs are computed using the distance between counties and power plants. Results from the transportation model including neighboring Idaho counties show that Utah can impose 5% mandatory rule to the power plants for producing electricity using the biomass co-firing. In cooperation of Idaho, the biomass co-firing is physically feasible for all the power plants in Utah at 5% co-firing ratio.

2.2. Cost of Biomass Co-firing

2.2.1. Levelized Cost of Coal-fired Electricity Generation

As alluded in previous sections, the cost of electricity generation using the biomass co-firing might be more expensive than using coal. The cost of electricity generation, typically \$/MWh, is calculated based on the initial capital and investment (building a power plant and a boiler), operating and maintenance costs (O&M), and fuel costs. A levelized electricity generation cost over time is used because the life of power plants is usually 20 - 40 years (Branker, Pathak & Pearce, 2011). A total levelized cost (LEC) is computed by:

$$LEC_{coal} = \left(\sum_t \frac{I_t + M_t + F_t}{(1+r)^t}\right) \Big/ \left(\sum_t \frac{E_t}{(1+r)^t}\right), \quad (4)$$

where LEC_{coal} stands for the average lifetime levelized coal-fired electricity generation cost, I_t is the investment expenditures, i.e., building a plant, in the year t (usually when $t = 0$), M_t is the operations and maintenance expenditures in t, F_t is the fuel (coal) cost, E_t represents electricity generation, and r is a discount rate. According to (US Energy Information Administration, 2012a), the estimated LEC of conventional coal-fired power plants is minimum \$91/MWh, average \$98/MWh, and maximum \$113/MWh.

2.2.2. Levelized Cost of Biomass Co-firing

The capital costs required for co-firing projects are usually lower than those of establishing new power plants or other renewable energy projects such as wind, solar and geothermal due to the fact that co-firing systems can be done on existing infrastructure of coal power plants (Highes, 2000). Costs related to co-firing (adapting coal-based power plant to co-firing) can be divided into a few groups such as i) capital costs – modification cost of boiler, ii) fuel costs – cost of biomass acquiring, saving coal cost and iii) additional operation and maintenance cost. For the biomass co-fring, the levelized cost may be given by:

$$LEC_{bmss} = \left(\sum_t \frac{I_t + I_t^B + M_t + F_t + B_t - saveF_t}{(1+r)^t}\right) \Big/ \left(\sum_t \frac{E_t}{(1+r)^t}\right), \qquad (5)$$

where $\mathrm{LEC_{bmss}}$ stands for the average lifetime levelized biomass co-fired electricity generation cost, $\mathrm{I_t^B}$ is the cost of modifying the existing boiler, $\mathrm{B_t}$ is the cost of biomass procurement which is the sum of biomass purchase and the biomass transportation cost as in equation (2), and $\mathrm{saveF_t}$ is the coal cost saving from the biomass co-firing. Thus, the additional LEC is given by $\left(\sum_t \frac{I_t^B + B_t - saveF_t}{(1+r)^t}\right) \Big/ \left(\sum_t \frac{E_t}{(1+r)^t}\right)$. Additional cost for 5% co-firing is now calculated for each power plant such that additional investment of boiler modification + cost of biomass purchasing and transporting + additional O&M cost – saving coal cost. Table 2 contains the results of additional levelized cost of biomass co-firing for the different power plants in the Utah.

Table 2. Additional Levelized Cost of 5% Biomass Co-firing ($/MWh)[a,b]

	Biomass Price Scenarios		
	$30/tonne	$40/tonne	$50/tonne
Bonanza	1.53	1.81	2.10
Carbon	1.46	1.75	2.03
Deseret	1.43	1.72	2.00
Hunter	1.57	1.85	2.14
Huntington	1.59	1.88	2.16
Intermountain	1.55	1.84	2.12
Smelter	0.74	1.03	1.31
Sunnyside	1.57	1.86	2.14
Average	1.43	1.72	2.00

Note: [a] Assuming blending system. [b] Specific cost numbers are not reported to save space, which are available upon request with references.

The results from Table 2 show that additional levelized cost of biomass co-firing for different power plants ranges from $1.03/MWh~$1.88/MWh assuming the biomass price is $40/tonne. According to US Department of Energy (2011), biomass prices of below $40/tonne for agricultural crop residues are not likely in the U.S. Thus, the biomass price of $40/tonne is assumed to have conservative estimations. The additional levelized cost for Smelter power plant is as low as $1.03/MWh comparing to other power plants. This is because Smelter power plant receives the biomass feedstock from the nearby Cache County. Bonanza, Hunter, and Sunnyside power plants receive most of their biomass feedstock from counties of Idaho, and thus the additional levelized costs are much higher than Smelter power plant paying more transportation costs.

The additional burden for different economic sectors is calculated using the additional cost of 5% biomass co-firing using numbers in Table 2. In year 2010, the residential sector in Utah consumed 8,834 GWh of electricity; commercial sector consumed 10,368 GWh, industrial sector used 8,808 GWh, and transportation sector utilized 38 GWh (Utah Geological Survey, 2011). The additional burden is calculated assuming each sector consumes the same amount of electricity. As shown in Table 3, the total additional cost of biomass ranges from $42.84 million to $58.86 million depending on biomass prices.

Table 3. Additional Cost of 5% Biomass Co-firing by Sectors (million dollars)

	Biomass prices		
Sectors	$30/tonne	$40/tonne	$50/tonne
Residential	13.50	16.02	18.54
Commercial	15.84	18.80	21.76
Industrial	13.46	15.97	18.49
Transportation	0.05	0.06	0.07
Total	42.84	50.85	58.86

One caveat should be mentioned. The numbers and parameters used in the derivation of the additional cost for the biomass co-firing are not deterministic. In other words, crop residue production is stochastic, cost parameters in transportation model are not fixed, coal price varies, and the discount rate might be higher or lower, and thus the additional cost to Utah is uncertain. The range analysis should be performed and derive a sort of distribution of the additional cost.

3. Biomass Co-firing Benefits

3.1. Greenhouse Gas Emission and Biomass Co-firing

Co-firing biomass with coal reduces GHG emissions (Hughes & Tillman, 1998; Battista, Hughes & Tillman, 2000). The biomass co-firing reduces CO_2 emissions by absorbing CO_2 during growth (photosynthesis) and emitting it at the time of combustion (Demirbas, 2003; Qin et al., 2006). Biomass is considered nearly a zero net CO_2 emission fuel source as it emits the same amount of CO_2 which they absorb during growth (Demirbas, 2003). Most of the researches on bio-energy production processes in the U.S. uses a life cycle assessment (LCA)[4] to quantify the overall environment impacts associated with a product or service, for example Qin et al. (2006), Mann and Spath (2001), and Sebastian et el. (2007). In this study, findings of Mann and Spath (2001), Sebastian et al. (2007), and (US Department of Energy, 2000) are used to estimate CO_2 emission reduction from replacing coal with biomass in the electricity generation (Table 4). As shown in Table 4, CO_2 emission may decrease by 2% to 6%.

Table 4. CO_2 Emission Reduction at 5% Biomass Co-firing

Sources	Emission Reduction	Emission Reduction Potential in Utah[a]
Mann and Spath (2001)	2.0%	0.63 million tons
Sebastian el al. (2007)	5.3%	1.66 million tons
U.S. DOE/EERE (2000)	6.0%	1.88 million tons

Note: [a] Utah CO_2 emission from coal-fired power plants in 2011 = 31.4 million metric tons of CO_2

[4] A life cycle assessment (LCA) is the way to quantify the GHG emission effect from the biomass co-firing. The LCA was created as “a valuable decision-support tool for both policy makers and industry in assessing the cradle-to-grave impacts of a product or process” (Global Development Research Center, 2004). Global Development Research Center (2004) specifies the LCA as “the assessment includes the entire life cycle of the product or service, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal.”

3.2. GHG Emissions and Economic Benefit of Biomass Co-firing in Utah

CO_2 emission from coal-fired power plants in Utah is estimated to be 31.4 million metric tons of CO_2 in the year 2011 (US Energy Information Administration, 2015). The last column of Table 4 shows that 5% biomass co-firing may reduce CO_2 emission in Utah by 0.63~1.88 million metric tons of CO_2. The economic benefit of reduction in CO_2 emission can be quantified assuming Utah can sell these reductions as the carbon credits in the carbon trading markets such as Chicago Climate Exchange (CCX) (now defunct) or European Emission Trading System (EU ETS).[5] Annual economic benefits from carbon trading are dependent upon the carbon price in the market. The current price of CO_2 in the EU ETS is about \$5/ton of CO_2 as of December 2013, which were maintained at around \$19-\$25/ton of CO_2 until around mid-2011. The Regional Greenhouse Gas Initiative (RGGI), another carbon trading market in the U.S., reports its carbon price of around \$3.3/ton of CO_2 (as of December 2013). Also, U.S. Environmental Protection Agency (EPA) uses the social cost of carbon to estimate the climate benefits. According to US Government (2013) the social cost of carbon is estimated to be higher than \$46/ton of CO_2 in the near future (year 2020) with 3% discount rate. Thus we have six different CO_2 price scenario from \$5 to \$50 in the near future.

Economic benefits from carbon trading are calculated based on CO_2 emission reduction potential in Table 4 and plausible carbon prices in the trading market discussed above. Table 5 contains the results. As shown in Table 5, economic benefits depend on the carbon price. A moderate economic benefit estimate would be \$8.3 million assuming \$5/ton of CO_2. The economic benefit rises to \$33.28 million in the near future (year 2020) with \$20/ton of CO_2 which is forecasted by (Luckow et al., 2013) assuming the mid case scenario, "federal policies are implemented with significant but reasonably achievable goals" (Luckow et al., 2013).

Table 5. Economic Benefit from CO_2 Trading (million dollars)

Emission Reduction	CO_2 price per ton of CO_2					
Studies and Potential	\$5	\$10	\$20	\$30	\$40	\$50
Mann and Spath (2011) – 2%	3.14	6.28	12.56	18.84	25.12	31.40
Sebastian et al. (2007) – 5.3%	8.32	16.64	33.28	49.93	66.57	83.21
U.S. DOE/EERE (2000) – 6.0%	9.42	18.84	37.68	56.52	75.36	94.20

3.3. Biomass Co-firing and Public Health Benefit

Coal-fired power plants directly emit particulate matters (PM) as well as other harmful air pollutants such as SO_2 and NO_x, which undergo chemical reactions to form fine particles in the atmosphere. These emissions increase the ambient concentration of PM less than 2.5 microns in diameter (PM25) and in the atmosphere over hundreds miles downwind of the power plants which depends upon the direction of the wind and the surrounding geography (Penney, Bell & Balbus, 2009). Recent epidemiological studies have shown that high levels of PM are closely correlated with substantial adverse health effects such as acute respiratory infections and mortality in the short-term (Chen et al., 2000; Pope, 2000; Pope, Burnett &

[5] Selling credits in EU ETS is unrealistic. In this study, we assume that there exists carbon credit market which regulates CO2 emissions in Utah, for example, California (neighboring state) carbon market.

Thun, 2002). Long-term exposure to the combustion-related PM and the SO_2-related air pollution could lead to cardiopulmonary and lung cancer (Viswanathan et al., 2006).

The biomass co-firing reduces harmful air pollutants such as PM. Many previous studies associated with biomass co-firing have focused on the feasibility and potential of biomass co-firing and implications of greenhouse gas emissions. It is rare, however, to investigate and quantify the benefit of reducing PM emission. We attempt to measure the monetary value of reducing PM emissions in terms of improving human health or avoiding adverse health incidents. These benefits are understood as the co-benefit (positive externality) of the biomass co-firing. According to Mann and Spath (2001) and Electric Power Research Institute (2003), PM emission reduction from replacing coal with biomass in the electricity generation is between 3% and 4.3% (Table 6).

Table 6. Particulate Matters (PM) Emission Reduction at 5% Biomass Co-Firing

Sources	Emission Reduction
Mann and Spath (2001)	3.0%
Electric Power Research Institute (2003)	4.3%

To measure the co-benefit of the biomass co-firing the following damage equation is introduced, $\mathrm{D} = \mathrm{f}(\mathrm{PM25}, \mathbf{x}) + \varepsilon$, where, D is the (monetary) health damage from PM25 emission including mortality, acute respiratory diseases (asthma, bronchitis), heart attack and work day loss[6]. The variable PM25 is the PM25 emission and **x** is a vector of other factors to affect the human health, e.g., population density, personal income, and weather conditions (e.g., wind speed and temperature) in a region where the power plant located. It is expected that the sign of PM25 is positive which implies more emission causes more health damage. To estimate damage, the health damage, PM25 emission and other relevant data are collected.

The health damage due to PM25 emitted from coal-fired power plants is collected from *Death and Disease from Power Plant* prepared by Clean Air Task Force (2010). The impact on human health, total health damage, is the sum of monetary expenses or estimated monetary losses due to the health damages from PM25 (Abt Associates, 2010). Abt Associates (2010) performed multiple steps for calculating monetary damages linked with PM25 emissions. First, PM25 emissions are calculated from the different electricity generation units, and, in turn, the impacts on ambient air quality were calculated. Second, using the epidemiological studies and literature to quantify the effect of PM25, adverse health impacts and number of incidents are estimated. Once the numbers of adverse health impacts are estimated, the economic damages associated these incidents are computed. For example, the mortality is evaluated for loss of $7.3 million, chronic bronchitis costs $440,000, and asthma ER visit evaluated for the loss of $370. Table 7 summarizes the total health damage due to PM25 emission estimates over regions.

Other explanatory variables are per capita income, population density, and weather variables such as average temperature and average wind speed, are included in the regression model because these factors may affect the public health impact. Per capita income was obtained from the U.S. Bureau of Economic Analysis. Population density was collected from the State and County Quick Facts in the U.S. Census Bureau Average temperature and average wind speed were collected from the Weather History, Weather Underground

[6] The health damages include mortality, acute bronchitis, heart attacks, asthma attacks, chronic bronchitis, asthma related emergency room visits, cardiovascular related hospital admission, respiratory related hospital admission, and also the acute illness and symptoms not requiring hospital admission such as lower respiratory system problems, upper respiratory system problems, minor restricted activity days and work loss days.

(http://www.wunderground.com/). Note that other explanatory variables are based on county level where the power plants are located.

Table 7. Regional Health Damage Due to PM25 Emission (Million Dollars)

Regions[a]	Total Health Damage	Number of Power Plants Reported	Health Damage per Power Plant	St.Dev.	CV	Max	Med	Min
East South Central	1,509.6	34	44.4	29.9	67.3	109.1	34.5	2.1
Rocky Mountain	1,329.0	30	44.3	47.2	106.5	146.5	19.3	2.2
West South Central	2,002.6	31	64.6	45.5	70.4	233.1	51.1	17.7
Pacific	124.0	4	31.0	35.4	114.2	78.3	21.4	2.8
New England	134.1	9	14.9	14.8	99.3	50.4	8.4	0.8
South Atlantic	3,405.6	88	38.7	37.9	97.9	166.0	24.2	1.8
East North Central	3,914.0	103	38.0	35.7	93.9	163.7	26.4	0.7
West North Central	1,938.8	74	26.2	28.5	108.8	129.7	13.6	0.8
Mid Atlantic	1,176.0	40	29.4	33.6	114.3	137.9	17.1	0.7
Utah	344.6	6	57.4	41.4	82.1	102.1	46.6	3.6

Note: [a] Regions: New England = CT, ME, MA, NH; Mid Atlantic = NJ, NY, PA; East North Central = IL, IN, MI, OH, WI; West North Central = IA, KS, MN, MO, NE, ND, SD; South Atlantic = DE, FL, GA, MD, NC, SC, VA, WV; East South Central = AL, KY, MS, TN; West South Central = AR, LA, OK, TX; Mountain (base region) = AZ, CO, MT, NV, NM, UT, WY; Pacific = CA, OR, WA

Regression results are reported in Table 8. As shown in Models 1, 2, and 3, PM25 emissions have a positive and statistically significant effect on the health damage. The health damage has the positive relationship with population density which is expected; the more people in the region, the more will be affected by PM25 emission and concentration, and thus the more health damage. Average wind speed has the negative effect which implies that a strong wind disperse the PM25 emissions quickly and lessens concentrations, and thus reduces health damage. The average temperature has the negative effect. This is because the excessive outside temperature restricts people in going outside, thus the estimated results have the negative sign.

Models in Table 8 have the similar estimates for PM25 emission 0.65 ~ 0.67. These estimates are interpreted as elasticity of the health damage with respect to the PM25 emission (log-log model). In other words, the public health would be improved by 0.65%~0.67%, or the monetary heath damage would be decreased by 0.65%~0.67%, when PM25 emissions were reduced by 1%. Combining PM25 emission reduction potential in Table 6, 5% biomass co-firing improves the human health by 1.95% ~ 2.88%. The annual economic benefit from PM emission reduction estimated as $6.72 million dollars ~ 9.93 million dollars by multiplying total health damage in Utah of $344.6 million in Table 7.

Table 8. Health Damage Regression Results (log-log model)

Health Damage	Model 1[a]	Model 2 Regional dummy	Model 3[b] State dummy
PM25 Emission	0.6697*** (0.039)	0.6549*** (0.030)	0.6728*** (0.033)
Pop Density	0.1878*** (0.037)	0.0336 (0.039)	0.0278 (0.422)
Per Capita Income	-0.4299 (0.429)	0.1584 (0.377)	0.0692 (0.372)
Average Temperature	-1.5589** (0.646)	-1.1953 (0.809)	-0.2934 (1.506)
Average Wind Speed	-0.4252***(0.143)	-0.1682 (0.150)	-0.0953 (0.151)
New England		0.1288 (0.437)	
Mid Atlantic		1.1801***(0.178)	
East North		1.3238***(0.159)	
West North		0.6614***(0.150)	
South Atlantic		1.1655***(0.165)	
East South		1.3187***(0.176)	
West South		0.4989** (0.237)	
Pacific		-1.2766***(0.195)	
Constant	13.4695** (6.367)	5.2681 (6.459)	6.4314 (8.193)
R^2	0.5347	0.6649	0.7505
F statistics (P-value)	70.12 (0.00)	80.82 (0.00)	152.88 (0.00)
Test for heteroscedasticity (Breusch-Pagan test and P-value)	χ^2 =16.18 (0.00)	χ^2 =1.15 (0.28)	χ^2 =0.39 (0.53)
No. of Obs.	356	356	356

Note: *** 1%, ** 5%, and * 10% significance level

[a] The standard errors are biased when heteroscedasticity is present. Robust standard errors are used to fix the problem.

[b] Model 3 includes state dummies which are not reported here to save space. State dummies: CT, ME, MA, NH, NJ, NY, PA, IL, IN, MI, OH, WI, IA, KS, MN, MO, NE, ND, SD, DE, FL, GA, MD, NC, SC, VA, WV, AL, KY, MS, TN, AR, LA, OK, TX, CA, OR, WA, AZ, CO, MT, NV, NM, WY (UT base region which was left out).

Table 9. Scenarios for Benefit-cost Analysis

Biomass Prices[a]	Carbon Prices[b]	Emission Reduction[c] (5% Biomass Co-firing)		
			CO_2	PM
$30/ton	$5/ton of CO_2	Low	2.0%	3.0%
$40/ton	$10/ton of CO_2	Medium	5.3%	3.7%
$50/ton	$20/ton of CO_2	High	6.0%	4.3%
	$30/ton of CO_2			
	$40/ton of CO_2			
	$50/ton of CO_2			

Note: [a] Based on Thompson and Tyner (2011), Mayer (2012), and US DOE (2011)

[b] Based on EU ETS and RGGI price records and price projection in Luckow et al. (2013); also US Government social cost of carbon (2013)

[c] Based on Mann and Spath (2001), Sebastian et al. (2007), and US DOE (2000)

4. Benefit Cost Analysis and Look-Up Table

Sections 2 and 3 discussed the additional cost of the biomass co-firing and economic benefits from the biomass co-firing including GHG and PM emission reduction. Benefit-Cost analysis is conducted to examine if the biomass co-firing in Utah is economically feasible under the various circumstances. Scenarios for benefit-cost analysis are constructed based on three components, i.e., biomass price, carbon price and amount of emission reduction from the biomass co-firing. A total of 54 scenarios are formed with three biomass prices ($30, $40 and $50), six carbon prices ($5, $10, $20, $30, $40, and $50), three emission reduction combinations [CO_2 emission reduction-PM emission reduction; 2%~3% (low), 5.3%~3.7% (medium), and 6%~4.3% (high)]. Table 9 summarizes all of these scenarios.

Economic benefits from the biomass co-firing under various scenarios are summarized in Table 10 using results from sections above. Economic benefits from the biomass co-firing are dependent upon carbon prices in the trading market and the amount of emission reduction from the biomass co-firing. With low CO_2 and PM emission reduction scenario and the low carbon price ($5/ton of CO_2), the economic benefit is estimated to be only $10.02 million (Table 10). The economic benefit rises to $13.16 million when the carbon price reaches $10/ton of CO_2 (Table 10). The economic benefit increases to $16.81~$25.13 million with the medium emission reduction scenario and rises even more with the high emission reduction scenario. In the year 2020, the carbon price is expected to increase up to $30/ton of CO_2 (Luckow et al. 2013) depending on energy consumptions, government policies and legislation, and international negotiations. The economic benefit rises to $41.77 million with $20/ton of CO_2 with the medium emission reduction scenario (Table 10) and to $75.06 million with $40/ton of CO_2 with the medium emission reduction scenario (Table 10).

Table 10. Economic Benefits From 5% Biomass Co-Firing in Utah (Million Dollars)

Emission Reduction	CO_2 price					
Potential	$5.00	$10.00	$20.00	$30.00	$40.00	$50.00
Low.CO_2	3.14	6.28	12.56	18.84	25.12	31.40
Low.PM	6.88	6.88	6.88	6.88	6.88	6.88
Low.Total	10.02	13.16	19.44	25.72	32.00	38.28
Medium.CO_2	8.32	16.64	33.28	49.93	66.57	83.21
Medium.PM	8.49	8.49	8.49	8.49	8.49	8.49
Medium.Total	16.81	25.13	41.77	58.42	75.06	91.70
High.CO_2	9.42	18.84	37.68	56.52	75.36	94.20
High.PM	9.87	9.87	9.87	9.87	9.87	9.87
High.Total	19.29	28.71	47.55	66.39	85.23	104.07

Benefit/Cost ratio of the biomass co-firing with various emission reduction scenarios (low, medium, and high) at different biomass and carbon prices are shown in Table 11. The biomass co-firing is economically feasible when the benefit cost ratio is greater than 1. That is highlighted in grey in Table 11. As shown in Table 11, the 5% biomass co-firing is economically feasible with high carbon prices, low biomass prices and high emission reduction potential (southeast corner of Table 11).

It is noteworthy that two key factors to make the biomass co-firing economically feasible are the emission reduction potential and the carbon price. If the biomass co-firing has the low emission reduction potential, it may not be economically feasible in general in Utah. If the biomass co-firing has the medium and high emission reduction potential, it would be economically feasible with moderate carbon prices (>$30/ton of CO_2). The most plausible estimate of the benefit cost ratio for Utah for now would be 0.331 assuming the medium emission reduction potential with biomass price of $40/ton and carbon price of $5/ton of CO_2. This is mainly because Utah has to pay high transportation costs. In the near future, if the carbon price rises to $30/ton of CO_2, the benefit-cost ratio would be 1.149 which passes the benefit-cost test.

Table 11. Benefit-cost Ratio of 5% Biomass Co-firing [a]

Emission Reduction Potential	Biomass Prices	CO_2 Price (per ton of CO_2)					
		$5	$10	$20	$30	$40	$50
	$50	0.170	0.224	0.330	0.437	0.544	0.650
Low	$40	0.197	0.259	0.382	0.506	0.629	0.753
	$30	0.234	0.307	0.454	0.600	0.747	0.894
	$50	0.286	0.427	0.710	0.993	1.275	1.558
Medium	$40	0.331	0.494	0.822	1.149	1.476	1.803
	$30	0.392	0.587	0.975	1.364	1.752	2.141
	$50	0.328	0.488	0.808	1.128	1.448	1.768
High	$40	0.379	0.565	0.935	1.306	1.676	2.047
	$30	0.450	0.670	1.110	1.550	1.989	2.429

Note: [a] Biomass co-firing is economically feasible when B/C ratio is greater than 1 that is in grey cells.

5. Conclusion and Future Studies

Various conclusions are extracted from this study. First of all, this article documents the way to build the benefit-cost ratio for biomass co-firing. Table 11 provides the benefit-cost ratio under the various circumstances such as biomass price, carbon credit price and emission reduction potential in U.S. semi-arid region, Utah. The procedure to build the benefit-cost ratio can be applied for any region with other scenarios suggested in this study. Second of all, the results of the transportation model show that Utah may not supply enough biomass feedstock for all of the coal-fired power plants in the state. Without making any further adjustment the biomass co-firing seems less feasible in Utah. One policy recommendation is to include southern Idaho counties.

In presenting this research, several limitations should be mentioned. The benefit-cost ratios reported in Table 11 is for Utah. To make the table for other regions, the transportation model should be reconstructed with new biomass supply, demand and distance data between supply regions and power plants locations. The transportation cost might be less or higher in other states or regions, even countries, according to the availability of biomass niches and supply regions. Second, benefits and costs of the biomass co-firing are subject to change because some of the parameters vary with the state and some of the parameters fluctuate with international market. For example, the price of coal, power plant operation days vary with the state while the price of CO_2 fluctuates with the international market. In addition, all the parameters are kept to be consistent in year 2011 value but the extension of the value to the near future may not be proportional and thus should be done with caution. Another limitation of this research is that it assumes that all the farmers participated in this program which may not be possible. It will depend on the incentive provided, or price of biomass.

The biomass co-firing may boost the rural economy (by providing an added opportunity for farmers) which is not discussed here due to the complication of the inter-industry relationship. Also, the biomass co-firing may cut back the production of coal mining sector which is not included here. Similarly, this research doesn't include the negative effect of biomass co-firing to the other sectors which are currently utilizing these biomass resources for example; cattle raising farms, hay making industries etc. These topics would be the future study. In addition, cost comparisons with other renewable energy sources should be done to achieve the regional RPS to promote the decision making processes.

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