Economics of Biomass Fuels for Electricity Production: A Case Study with Crop Residues

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Abstract

In the past, studies on agricultural feedstocks for energy production were motivated by rising fossil fuel prices interpreted by many as caused by resource depletion. However, today's studies are mainly motivated by concerns for climate change and global warming. Currently, most studies concentrate on liquid fuels with little study devoted toward electricity. This study examines crop residues for electricity production in the context of climate change and global warming. We use sector modeling to simulate future market penetration for biopower production from crop residues. Our findings suggest that crop residues cost much more than coal because they have lower heat content and higher production/hauling costs. For crop residues to have any role in electricity generation either the carbon or carbon dioxide equivalent greenhouse gas price must rise to about 15 dollars per ton or the price of coal has to increase to about 43 dollars per ton. We find crop residues with higher heat content and lower production costs such as wheat residues have greater opportunities in biopower production than the residues with lower heat content and higher production costs. In addition, the analysis shows that improvements in crop yield do not have much impact on biopower production. However, the energy recovery efficiency does have significant positive impact but only if the carbon equivalent price rises substantially. The analysis also indicates the desirability of cofiring biomass as opposed to 100% replacement because this reduces hauling costs and increases the efficiency of heat recovery. In terms of policy implications, imposing carbon emission pricing could be an important step in inducing electric power producers to include agricultural biomass in their fuel-mix power generation portfolios and achieve greenhouse gas emission reductions.

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1 Introduction

During the energy crisis in the late 70's, increased interest in biofuels was stimulated by rising oil prices. Biofuels were seen as a way to protect against the rising fossil fuel prices and the political insecurity of foreign energy supply. Biofuels related concerns and interests subsided following the sharp decline of oil price in the mid 80's. Like the 70's, today's increase in oil prices has again stimulated interest in using biomass for energy production. Energy security concerns are also prominent. Furthermore, growing evidence suggests that combustion of fossil fuels is a causal factor behind climate change (Intergovernmental Panel on Climate Change, 2007). Thus, at present there are three factors which may influence the prospects for bioenergy: 1) increases in crude oil prices, 2) concerns for national energy security matters and 3) concerns for climate change and global warming.

This paper focuses on the use of agriculturally related biomass for electricity production which we will call biopower from here on. Increases in oil and gas prices and concerns for energy security in the U.S. may not matter much in inducing electric producers to use biopower. This is because fuel oil accounts for only about 3 percent of the U.S. electricity generation (Table 1) and most of the required fuels used to generate electricity are available within the country. Also due to the possibility of inter-fuel substitutions among various fuel sources in electricity production, any increases in oil and gas prices will induce power producers to switch other fuel sources especially coal which is abundantly available (Sweeney, 1984). Hence, we feel that currently the main driving force that would stimulate interest in biopower is concern for climate change and global warming and will study ways this might happen.

Power plants are among the biggest sources of GHG emissions in the U.S. The electric power sector emits about 38 percent of the total U.S. carbon dioxide (CO_2) emissions from all sources (EPA, 2006). Burning coal produces more CO_2 than any other method of generating electricity, with coal used to generate more than half of the electricity in the U.S (Table 1). Biomass that could be used to fuel electric power plants or heat producing processes include agricultural crop residues, forest residues, energy crops, urban wood wastes, and animal manure. We examine crop residues in this paper.

Prior case studies on the economic feasibility of crop residues for biopower production were motivated by the concerns for rising fossil fuel prices interpreted by many as caused by resource depletion (Hitzhusen and Adallah, 1980; English et al., 1981). Many of the recent studies on biopower are mainly motivated by the concerns for climate change and global warming (Graham et al., 1995; Hall and House, 1995; Perlack et al., 1995; Hughes and Tillman, 1998; and McCarl et al., 2000). To the best of our knowledge, to date there exists few studies which focus on crop residues for biopower production in the context of climate change and global warming. The purpose of this paper is to fill the gap in the existing literature by examining the relationship between biopower production from crop residues and carbon equivalent GHG prices. Specifically, this paper addresses the following issues:

1) Would crop residues have any role in biopower production? This will be examined with and without future increases in coal and carbon equivalent prices.
2) How do changes in heat recovery form and production costs of crop residues affect biopower production?
3) How much of a reduction in residue production costs has to be achieved for biopower to have market potential with and without consideration of carbon prices?
4) Would changes in crop yield and fuel conversion efficiency technology have impacts on the production of biopower from crop residues?

In analyzing the above questions, we simulate future market conditions of biopower production from crop residues under various alternative scenarios. The Forest and Agricultural Sector Optimization Model—Green House Gas version (FASOMGHG) is employed to do the empirical parts of this work simulating future market scenarios for biopower production from crop residues (Adams et al., 2005). FASOMGHG is designed to simulate activity over a long period of time. In this paper, biopower production is simulated from the year 2000 to the year 2045 in five year intervals. Both co-fire and fire-alone options are examined in the analyses. Six crop residues – corn, wheat, sorghum, oats, barley and rice residues – will be considered in the analyses.

The rest of the paper is organized as follows. First the impact of crop residues removal on soil erosion is examined. Next, we analyze how crop residues are produced and how their production costs are generated. Then, we describe the model used in this paper –FASOMGHG. After that, the prospects for crop residues are studied. Using FASOMGHG under various alternative scenarios, the final section simulates future biopower production from crop residues. Simulation results are interpreted and then summary and conclusion are provided.

2 Effects of Crop Residue Removal on Crop Production

Not all agricultural crop residues are available for energy production, because some must remain in the field for soil erosion control, maintenance of soil organic matter[3] (SOM) and maintenance/enhancement of soil carbon (C). Moreover, surface crop residues reflect light and protect soil from high temperatures and evaporative losses (Sauer et al., 1996).

2.1 Relationships between Crop Residue Removal, Soil erosion, SOM Concentration and Carbon Emissions

The value of crop residues for erosion control and soil fertility maintenance has been well documented for all agricultural regions in the U.S. (Larson, 1979). Residues control erosion by reducing the impact of wind and water on soil particles. Erosion would increase significantly if crop residues were totally removed. In turn increased erosion would reduce soil fertility by carrying away nutrients in the soil sediments and deplete the soil organic carbon (SOC) pool (Holt, 1979; Lal, 2003; Pimentel et al., 1981). Lal et al. (1998) estimated that soil erosion by water leads to an emission of 15 million metric ton (MMT) of C per year from the U.S. soils. Thus, reducing emissions of GHG from agriculture is related to increasing and protecting SOM concentration (Jarecki and Lal, 2003).

Removal of crop residue has a rather small direct impact on SOM concentration. According to studies (see Campbell et al., 1991; Balesdent and Balabane, 1996; Gale and Cambardella, 2000; Flessa et al., 2000; Wilhelm et al., 2004), only a small portion of the

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[3] SOM plays a crucial role in the development and maintenance of fertility through the cycling, retention, and the supply of plant nutrients, and in the creation and maintenance of soil structure (Swift, 2001).

residues added to soil are converted to SOM. Roots contribute most of the SOM, because roots have a slower decay rate, are well-placed within the soil and are continually dying and discharging materials in soil. Aboveground crop residues take on importance as they diminish soil erosion which protects SOM concentration.

2.2 Tillage Effects on SOM concentration, Carbon Emissions and Residue Removal

Soil tillage practices affect the concentration of SOM. The influence of tillage on SOM dynamics is also well documented (Paustian et al., 1997; Lal, 2001; Jarecki and Lal, 2003). Immediately after plowing the exposure of SOM or SOC to oxidization cause large losses of CO_2 released into the atmosphere (Reicosky and Lindstrom, 1993; Al-Kaisi, 2001). There are different levels of tillage intensity and these are often grouped into two classes: conservation tillage (no tillage or reduced tillage) and conventional tillage. Conservation tillage reduces the frequency and intensity of tillage, retains crop residues as mulch on the soil surface, reduces the risks of runoff and soil erosion, increases the SOC content of the surface soil, and reduces CO_2 emissions (Lal and Kimble, 1997; Reicosky, 1999; Al-Kaisi and Yin, 2005). Moreover, conservation tillage with residue cover usually results in less soil erosion than conventional tillage, highlighting the importance of tillage-residue interaction when assessing the effects of residues on soils (Benoit and Lindstrom, 1987; Andrews, 2006).

Hooker et al. (2005) show that removing corn residues under conservation tillage system does not affect SOC storage, however when conventional tillage system is employed, removing corn residues negatively affects SOC storage. So, the specific quantities of residue that could be safely removed without affecting soil erosion and SOC concentration vary with tillage management practices. Greater amounts are available with conservation tillage than with conventional tillage. A study of the U.S. Corn Belt indicates that by shifting from conventional tillage to conservation tillage, the recoverable residues could be increased significantly (Lindstrom et al., 1979; Hall et al., 1993). Although conservation tillage systems have advantage over conventional tillage systems, historically conventional tillage systems are more commonly practiced (Uri, 1999). According to Kurkalova et al. (2006), this could be due to the uncertainties and lost profits associated with adopting a conservation tillage practice which requires investment in physical and human capital. Conservation tillage systems are more often practiced in the area where farmlands are highly erodable (see Uri, 1999).

3 Harvestable Crop Residues for Energy Generation

The maximum amount of crop residue which can be removed without affecting soil erosion depends on many site specific factors such as soil type and fertility level, slope characteristics, tillage system, climate and crops. Moreover, the opportunity cost of using residues has to be considered in the residue removal decision making process. Generally, USDA, National Resources Conservation Service (NRCS) recommends that about 30 percent residue cover is adequate to control soil erosion. Most studies have centered on the removal of corn stover. Calculations have been made for the U.S. Corn Belt on the amount of residues needed to bring erosion below the soil loss tolerance level.[4] According to Hall et al. (1993), the fraction of residues that can be removed with conventional tillage practices averages 35 percent for the Corn Belt as a whole. Nelson (2002) and McAloon et al. (2000) indicate that the actual amount of corn stover that could be removed ranges from 20% to about 30% of the total based on the need for adequate soil cover to control erosion.

Hettenhaus et al. (2000) argued that on average about 50% to 60% of corn stover was likely to be available depending on the regional slope characteristics. Haq (2002) suggested that depending on the State, about 30% to 40% of agricultural residues could be removed from the soil. Campbell et al. (1979) calculated the crop residues needed for water erosion control in six southern states which include Alabama, Georgia, Mississippi, North and South Carolina, and Virginia. In four of six states, 60% of the crop residues were needed for water erosion control. About 90% of the residues were required for water erosion control in Alabama and Mississippi. Recently, Perlack et al. (2005) derived the national estimates of average crop residue removal rates for corn and wheat based on various tillage scenarios. They showed that the removal rates for corn were 33 percent, 54 percent and 68 percent respectively under conventional tillage,

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[4] Soil loss tolerance level is defined by the USDA as the maximum level of soil erosion that will permit high crop production to be maintained economically and indefinitely.

reduced tillage and zero tillage systems. For wheat, the removal rates were 14 percent, 34 percent and 48 percent respectively under conventional tillage, reduced tillage and zero tillage scenarios. These results are consistent with the finding of Lindstrom et al. (1979), which indicates that by shifting from conventional tillage to conservation tillage, the removable rate of residue could be increased significantly. On the other hand, in their recent review, Mann et al. (2002) did not give recommendation of harvestable residue, recognizing research is still needed to project long-term effects of residue harvest on soil and water quality, SOC dynamics and storage etc. (also see Wilhelm et al., 2004).

3.1 Method of Estimation, Assumptions and Data Need

3.1.1 Crop Residue Production

For the residues, six crops will be considered: corn, sorghum, wheat, oats, barley and rice. Following Nelson et al. (2004), the quantities of residues that can be removed for energy generation or other purposes can be estimated as,

$$R_{rem} = R_{prod} - R_{min} \tag{1}$$

R_{rem} is the quantities of residues that can be removed from agricultural lands. R_{prod} is the amount of residue produced. It can be calculated as follows,

$$R_{prod} = Grain\ Yield \times Weight \times SGR \tag{2}$$

where total residue production is measured in wet tons. Grain yield is the weighted average yield of grain crop in bushels per acre. Grain yield data for Weight is the weight of grain in tons per bushel which can be converted from pounds per bushel. SGR is defined as a straw-to-grain ratio. For instance, SGR for rice is about 1.5 which means for every kilogram of rice yield, the yield of straw is 1.5 kilogram. To compute the residue production (R_{prod}) data for crop yield, weight and SGR will be needed. Both grain yield and weight data for the six crops were obtained from the USDA web site.[5] The yield data are based on the year 2001. While the data for SGR were collected from the following literature: Tyner et al. (1979) and Lal (2005). The values of SGR, weight and related moisture content for the six crops are reported in Table 2.

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[5] http://www.nass.usda.gov.

Finally, R_{min} is denoted as the minimum amount of residue that must be retained in the field each year to protect soil erosion. Developing a single national estimate of the minimum amount of residue that must remain on the ground to maintain soil sustainability is rather challenging, as one will require detail knowledge in the area of soil fertility, soil erosion, land characteristics and tillage and cropping systems. Residue maintenance requirements are most properly estimated at the individual field level with models such as Revised Universal Soil Loss Equation (RUSLE) used together with the Soil Conditioning Index (SCI) tool (Perlack et al., 2005). But, as suggested in Perlack et al., (2005), using this approach to compute a national estimate would require actual data from hundreds of thousands of specific locations. Fortunately, Nelson (2002) and Nelson et al. (2004) developed a methodology for making a national estimate that reflected the RUSLE/SCI modeling approach in that it considered soils, rainfall, crop rotation and tillage choices in determining the amount of residue required to minimize erosion to tolerance levels.

Based on the approach of Nelson (2002) and Nelson et al. (2004), Perlack et al., (2005) derived the national estimates of average crop residue removal rates for corn and wheat under three tillage scenarios – conventional tillage, reduced tillage and zero tillage. As mentioned in the section above, the removal rates for corn were 33 percent, 54 percent and 68 percent respectively under conventional tillage, reduced tillage and zero tillage scenarios and for wheat they were 14 percent, 34 percent and 48 percent respectively. By using these national estimates of residue removal rates, R_{min} were computed for corn and wheat. For the remaining four crops – sorghum, barley, oats and rice, the same removal rates of wheat were used to compute R_{min}. Research in this paper is conducted at a national level. The total quantities of crop residues available in each State are estimated using grain production, straw to grain ratio, weight, and moisture content.

3.1.2 On Farm Production Cost

Before delivering biomass residues to electric power plants, they first have to be harvested and collected. Harvest and collection includes gathering and removing crop residues from field. The harvest and collection method is a three-step procedure which can be illustrated as follows (DOE, 2003).

Cut and Windrow → Bale and Package → Move to Field Edge for Storage

First, grains are harvested and the biomass residues are cut and/or shredded. Cutting and/or shredding may be necessary because some of the biomass plant will be in stalks anchored to the ground after grain harvesting. The anchored pieces of biomass are difficult to cut and bale in a single operation. Large pieces of biomass would make better bales but shredding followed by spreading will accelerate field drying (Sokhansanj and Turhollow, 2002). The spread biomass may need to be windrowed depending on the situation to facilitate baling. Second, a baler (either self-pull or pulled by a tractor) picks up the residues, compacts and packages the residues in a bale. Bales can be in the form of either rounds or squares. Large round bales are applied in the analysis, because round bales are widely used in existing haying operations and they are popular on most U.S. farms (Sokhansanj and Fenton, 2006). Finally, bales are moved to the field edge or road side for temporary storage. The stacks of collected biomass at the road side will be picked up and transported to their destination.

Using an engineering-economic approach, Turhollow et al. (1998) estimated in-field costs for collection and movement to field edge of corn and small grain residues. Based on different crop residue yield assumptions, they showed that on average (weighted by the yield), it would cost about $15.91 per ton for corn residues and $10.42 per ton for small grain residues to be collected and removed to the field edge. The in-field operation costs include the costs of mowing, raking, baling, moving to road side, and twining. Similarly, by employing an engineering-economic approach, Sokhansanj and Turhollow (2002) estimated the cost of collecting corn stover to be around $14.1 per ton. This covers shredding, baling, stacking and twining costs. Perlack and Turhollow (2002) calculated corn stover collections costs (which include baling, moving bales to storage, stacking bales and storage) for an ethanol conversion facility. They showed that on average it would cost about $24.47 per ton to collect and store corn stover.[6] Summers (2001) estimated that rice straw removal costs were about $ 17.69 per ton for on-field operations which include swathing, raking, baling and moving to road side. He also showed that storage and grinding operations would add more costs to the rice straw, about $13.54 per ton. Following the study of Turhollow et al. (1998), in this paper on-farm collection costs are assumed to be fixed and equal to $15.91 per ton for corn and sorghum residues and $10.42 per ton for small grains such as wheat, barley and oats. For rice residues, collection costs are assumed to be $ 17.69 per ton as indicated in Summers (2001). In addition, storage and processing costs of $13.54 per ton will be assumed. These on-farm collection costs, storage and processing costs, and transport/hauling costs (discussed below) will be incorporated into the FASOMGHG.

3.1.3 Hauling Cost

Transportation is a key segment of the biomass feedstock supply system industry. Biomass may be transported by truck on existing roads or by trains and barges on existing rail networks and waterways (DOE, 2003). It is assumed that biomass is transported to a power plant by truck, since truck transport is generally well developed and is usually the cheapest mode of transport but it becomes expensive as travel distance increases (Sokhansanj and Fenton, 2006). Transport costs which cover the distance from the farm gate to the plant gate are an important part of total costs. They are increasing function of distance and depend on the yield and density of crop residues, the size of biomass power plant and a given truck-hauling rate (Gallagher et al., 2003). The cost of transporting biomass is often the factor that limits the size of a power plant. Larger power plants can benefit from economies of scale and lower unit capital costs. However, the dispersed nature of biomass residues, and relatively low efficiencies of available conversion systems have tended to limit the size of existing electricity producing plants to a maximum size of 100-150 megawatt (MW) (Larson, 1993).

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[6] Transport cost from the storage area to ethanol conversion facility is excluded.

Following McCarl et al. (2000), the power plant size in this study is assumed to be a 100 MW plant which requires seven trillion BTUs (7 TBTUs) of feedstock per year. Based on an approach by French (1960) as described in McCarl et al. (2000), transport/hauling costs (TC) per ton of biomass residues are calculated as follows:

(3) $$TC = \frac{Fixed\ Cost + (2 \times \overline{D} \times Cost\ per\ Mile)}{Loadsize}$$, where

$$\overline{D} = 0.4714 \times \sqrt{\frac{M}{(640 \times Den \times Yld)}}$$

Given a square grid system of roads as described in French (1960), $\overline{D}$ is denoted as an average hauling distance in mile(s) which depends on a 100 MW power plant requirement of M tons of biomass (equivalent to 7 TBTUs of feedstock), the density (Den in %) of biomass residue production and a harvestable residue yield (Yld) in ton(s) per acre. The factor “640” represents the number of acres in a square mile. The required M tons or 7 TBTUs of biomass crop residues can be computed using the heat content of each crop residue (Table 3). All crop residues are assumed to have moisture content and all units are based on the wet matter content. The density of each crop residue in percent is calculated by dividing total harvested acres of each crop by total land area in acres. Fixed cost includes loading and unloading costs and the cost of operating a truck. The number “2” represents round trip and cost per mile is a cost for each mile of the trip. Loadsize is an average load size of a truck load in weight hauled. Fixed cost and cost per mile are assumed to be \$90 and \$2.20 respectively.[7] Finally, the load size of a truck is assumed to be 20 tons.

4 Model Description

All of the above aforementioned method of estimation, assumptions and data are incorporated into the Forest and Agricultural Sector Optimization Model—Green House Gas version (FASOMGHG). It is a dynamic, nonlinear programming model of the forest and agricultural sectors in the U.S. The model simulates the allocation of land over time

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[7] Fixed cost and cost per mile are obtained by Dr. Jerry Cornforth’s personal communication with Dr. Shahab Sokhansanj, Agricultural Engineer, Environmental Sciences Division of Oak Ridge National Laboratory.

to competing activities in both the forest and agricultural sectors and the resultant consequences for the commodity markets supplied by these lands and, importantly for policy purposes underlying the development of this model, the net greenhouse gas (GHG) emissions. The model was developed to evaluate the welfare and market impacts of public policies that cause land transfers between the sectors and alterations of activities within the sectors.

To date, FASOMGHG has been used to examine the effects of GHG mitigation policy, climate change impacts, public timber harvest policy, federal farm program policy, biofuel prospects, and pulpwood production by agriculture. It can also aid in the appraisal of a wider range of forest and agricultural sector policies. FASOMGHG is an outgrowth of a number of previous lines of work (see details in Adams et al., 2005). One of the primary roots of FASOMGHG involves efforts by McCarl and colleagues to use sector modeling to appraise the economic and environmental implications of environmental and agricultural policy-related developments within the agricultural sector.

4.1 Overall FASOMGHG Model Structure

Operationally, FASOMGHG is a dynamic, nonlinear, price endogenous, mathematical programming model. It is dynamic in that it solves for the simultaneous multi-market, multi-period equilibrium across all agricultural and forest product markets, for all time periods, and thus for the inter-temporal, inter-sectoral land market equilibrium. FASOMGHG is nonlinear in that it contains and solves a nonlinear objective function to maximize net market surplus, represented by the area under the product demand function (an aggregate measure of consumer welfare) less the area under factor supply curves (an aggregate measure of producer costs). The resultant objective function value is consumers' plus producers' surplus. FASOMGHG is price-endogenous because the prices of the products produced and the factors used in the two sectors are determined in the model solution. Finally, FASOMGHG is a mathematical programming model because it uses numerical optimization techniques to find the multi-market price and quantity vectors that simultaneously maximize the value of an objective function, subject to a set of constraints and associated right-hand-side (RHS) values that characterize: the transformation of resources into products over time; initial and terminal conditions; the availability of fixed resources; generation of GHG net emissions; and policy constraints.

Since the objective function of FASOMGHG depicts maximization of the net present value of producers' and consumers' surpluses, associated with production and price formation in competitive markets over time for both agricultural and forest products, the first-order (Kuhn-Tucker) conditions for the choice variables in the model provide a set of optimization rules for economic agents to follow, leading to the establishment of a competitive equilibrium. Because these choices occur over time, the optimizing nature of the model holds that producers and consumers' have perfect foresight (the assumption that agents are rational and respond with the best information they have available at the time) regarding future demand, yields, technologies, and prices. In other words, choices made at the beginning of the projection period are based on correct expectations of what the model predicts will occur in the future. Thus, FASOMGHG incorporates expectations of future prices. Farmers and timberland owners are able to foresee the consequences of their behavior (when they plant trees or crops) on future agricultural product and stumpage prices and incorporate that information into their behavior.

FASOMGHG is typically run as a 100-year model depicting land use, land transfers, and other resource allocations between and within the agricultural and forest sectors in the U.S. The two sectors are linked through land transfer activities and constraints. Given the modeling of multiyear timber production, FASOMGHG needs to handle economic returns over time. This is done by solving for multiple interlinked market equilibria in adjacent five year periods for the model duration, rather than for just one single period (as would be the case in a static equilibrium model). Hence, the model solution portrays a multi-period equilibrium on a five year time step basis. The results from FASOMGHG yield a dynamic simulation of prices, production, management, consumption, and GHG effects within these two sectors under the scenario depicted in the model data.

FASOMGHG reflects the mobility of the land resource between the forest and agriculture sectors subject to controls for land quality/growing conditions, investments needed to mobilize land, and hurdle costs consistent with observed behavior. The land quality factors generally restrict some lands to only be in forest, due to topography or soil characteristics. Likewise, the growing conditions render some lands unsuitable for forest uses at all, particularly in the drier plains areas of the country, and would thus be suitable only for some agricultural uses. The investments to mobilize land from forest to agriculture generally involve stump clearing, leveling, etc. of forested lands and result in a three step depiction of land transformation processes. The hurdle costs reflect costs to move land between uses.

FASOMGHG also reflects movement of commodities between the forest and agriculture sectors, largely in the form of short rotation woody crops. In particular, agriculturally produced short rotation poplar can be chipped and move into pulp and paper production processes and milling residues, pulp logs and in some cases logging residues can move between sectors as raw material sources for finished products made in the other sector. All agricultural sector models, where great heterogeneity of growing conditions, resource quality, market conditions, and management skills are present, must deal with aggregation and calibration. The aggregation problem involves treating groups of producers operating over aggregated resource sets as homogeneous units. The calibration problem involves dealing with spatially disaggregate producers who are entrants in a single market but receive different prices.

4.2 Crop Production in FASOMGHG Regions

Geographically, FASOMGHG regions cover forest and agricultural activities across the U.S. The crop production set is defined at the 63 region level and currently there are more than 1200 production possibilities. Yields, costs and input usage rates vary by region. These include major field crop production, livestock production, and crop residue or energy crop feedstock production. Also, they are defined across multiple land types (wet land, low erodible crop land, medium erodible crop land, and severely erodible crop land), irrigation possibilities (irrigated and non-irrigated), fertilization alternatives (three alternatives – base fertilization then 15% and 30% reductions from the base) and tillage alternatives (three alternatives – conventional, reduced and zero). Yield, water use, and erosion data for these alternatives are defined based on runs of the EPIC (Erosion Productivity Impact Calculator) crop growth simulator.

For the purpose of simplifying our analyses, all the yield and crop residue production data based on different land types, irrigation possibilities and tillage alternatives are aggregated and broken down from 63 sub-regions into 11 market regions for agricultural sector coverage as shown in Table 4. Research in this thesis will be conducted at the 11 region level. The 11-region breakdown reflects the existence of regions for which there is agricultural activity but no forestry, and vice versa. Forestry production occurs in nine of the 11 production regions, but agricultural sector activity cannot be reasonably condensed to only these nine regions. For instance, the Northern Plains (NP) and Southwest (SW) regions reflect important differences in agricultural characteristics, but no forestry activity is included in either region. Likewise, there are important differences in the two Pacific Northwest regions (PNWW, PNWE) for forestry, but only the PNWE region is considered a significant producer of the agricultural commodities tracked in the model.

5 Analysis of Crop Residue Prospects

Besides their uses in energy generation, crop residues have an important role in soil erosion control and maintenance of soil organic matter. As discussed above, the amount of crop residues which can be removed for energy generation will depend on many factors such as soil type and fertility level, slope characteristics and tillage system. Based on the studies of Nelson (2002), Nelson et al. (2004) and Perlack et al. (2005), the amount of removal crop residues is established in FASOMGHG. In addition, following a method by French (1960) as described in McCarl et al. (2000), residue density, hauling distance and hauling cost are estimated in FASOMGHG. Furthermore, crop residue delivered costs which include harvesting, processing, storage and hauling costs are also computed.

5.1 Characteristics of crop residue supply

The supply of crop residues for electricity generation will rest on a number of factors which are described below.

5.2 *Availability of Crop Residues for Power Generation*

All estimated results are aggregated from 63 sub-regions into 10 agricultural regions[8] as defined in FASOMGHG. Using equation (1), the amount of removable crop residues available for energy generation is estimated in FASOMGHG based on different land types, irrigation possibilities, and fertilization and tillage alternatives. These estimated aggregated results of removable crop residues in the 10 agricultural regions for six crops are shown in Table 5. Total amount of harvestable crop residues in million tons (Table 7) are obtained by multiplying the amount of removable crop residues in tons per acre with total harvested acres (Table 6) of each crop in each region. Nationally about 156 million tons of crop residues are available with 68% of them coming from the CB and GP regions and 93% of them are accounted for by corn and wheat residues (Table 7). About 116 million tons of corn residues and 30 million tons of wheat residues can be harvested nationally and are enough to supply 217 100MW power plants.[9]

5.3 *Average Density and Distance of Crop Residues*

One of the main factors that influence the spread between farm level costs and industry level (delivered plant) costs is the density of residue (Gallagher et al., 2003). Lower crop residue density will result in higher distance traveled between farm land and delivered plant. This in turn will result in higher hauling costs as indicated by equation (3). The density of crop residue in each region (in percent) can be obtained by dividing total harvested acres of each crop in each region by total land area of that region in acres. The estimated results of crop residue density (Table 8) are aggregated from 63 sub-regions into 10 agricultural regions as defined in FASOMGHG. As expected, the table shows that corn residues are densely concentrated in CB region, while wheat, sorghum and barley residues are highly concentrated in the GP region.

Average hauling distance between farm land and bioenergy plants (see equation (3)) is a function of density, yield and required tons of crop residues (which

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[8] One region (PNWW) is ignored because it is not agriculturally significant in FASOMGHG.

[9] Here we are making the assumptions that crop residues are costless and that a 100 MW power plant requires 7 TBTUs equivalent of crop residues each year for power generation. By using HHVs and the required tons of corn and wheat residues for a 100 MW power plant, the number of 100MW power plants can be calculated.

contains recoverable BTUS equivalent to 7 TBTUs for a 100 MW power plant). The estimated aggregated results for average hauling distance are displayed in Table 9 and Table 10 for corn and wheat residues respectively (Results for sorghum, oats, barley and rice residues are not reported). The results are reported for the 10 agricultural regions in the U.S., and for various cofire (5%, 10%, 15% and 20%) and fire alone (100%) scenarios. Data in the tables suggest that as cofire ratios increase i.e. as a 100 MW power plant consumes more and more crop residues, average hauling distance increases at an increasing rate since residues will have to be collected from longer distances[10]. Table 9 indicates that among the 10 agricultural regions, CB has the lowest average hauling distance for corn residues, because the concentration (density) of corn residues is the highest there. Similarly in Table 10, GP has the lowest average hauling distance for wheat residues as the concentration of wheat residues is the highest in that region.

5.4 Average Hauling Cost

Average crop residue density and subsequently hauling distance will be important in determining average hauling cost between the supply point and the demand point of crop residues, as indicated in equation (3). The estimated average hauling costs for the 10 agricultural regions in different levels of cofire and fire alone ratios are shown in Table 11. As mentioned above, among the 10 agricultural regions, CB has the highest corn residue density which means the hauling distance between farm land and delivered plant in that region will be the lowest. This will yield the lowest hauling cost for corn residues in CB (Table 11). The same thing can be said about wheat and other residues (see Table 12 for wheat residues, the tables for other crop residues are not reported). In PNWE, on average it would cost about $72 per ton for cofire power plants to acquire corn residues as the concentration of corn residues is the lowest in that region and power generators would have to travel greater distances to collect corn residues. In addition, it would not be feasible at all to fire corn residues alone (100%) in a power plant in that region because the cost of hauling would be prohibitively high. Obviously, hauling cost for crop residues will be lower in a region where residue concentration is high than in a region which has a low concentration of residues.

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[10] The distance is based on the square system as described in French (1960).

5.5 Total Crop Residue Production Cost

Flaim and Hertzmark (1981) estimated that on average the total cost of crop residues delivered to electric utility would be about $34.33 per ton which include costs of harvesting, storing and hauling. Turhollow et al. (1998) assessed the delivered costs of corn and small grain residues to be around $21.79 per ton and $16.3 per ton respectively. Their delivered costs included harvesting and hauling costs[11], but storage and processing costs were ignored in their study. In the same way, Sokhansanj and Turhollow (2002) evaluated harvesting and hauling costs[12] of corn stover to be around $19.6 per ton, but they did not take storage and processing costs into consideration in their evaluation. Perlack and Turhollow (2002) showed that on average corn stover could be collected, stored and hauled[13] for about $45.83 per ton using conventional equipment for ethanol conversion facilities of different sizes.

In this paper, costs of harvesting and collecting, storing and processing based on the literature (as discussed above) are used along with the estimated hauling costs and the farmer payments[14] to derive the estimates for average crop residue delivered costs in dollars[15] per ton (Table 13 and Table 14). As can be seen in the tables, estimated results are more or less consistent with the literature. On average, it would cost about $50 per ton for a biomass-fire-alone 100MW power plant to acquire corn residues in CB. As for wheat residues with fire-alone option, it would cost about $49 per ton in GP. Cofiring crop residues with coal may be a better option for power generators as crop residues are cheaper with cofire options than with fire-alone option.

5.6 Cost Comparisons between Crop Residues and Coal

In order to compare average delivered costs between crop residues and coal, all cost units in ton are converted into the same common energy units in million Btu (MMBtu) by employing the heat content of the respective fuels. For instance, an average wheat residue delivered cost of $49 per ton can be converted into $3.25 per MMBtu by using the wheat

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[11] The hauling cost was assumed to be fixed at $5.88 per ton.

[12] Their estimated hauling cost was around $5.53 per ton.

[13] The calculated average hauling cost and hauling distance in their study are about $9.18 per ton and 38 miles respectively.

[14] Based on Perlack and Turhollow (2002), farmer payments of $10 are assumed.

[15] Note all costs are based on 2004 dollars.

residue heat content of 15.06 MMBtu per ton. The same thing can be done with coal by using its respective heat content. All average delivered costs of coal, corn and wheat residues converted from their respective units in ton to a common unit in dollars per MMBtu are reported in the tables below (Table 15, 16 & 17). As suggested in the tables, coal prices have been stable and below $2 per million Btu in most of the regions and crop residues are not cost competitive with coal for both cofire and fire-alone options. Coal prices will have to rise much higher than the current level in order to make crop residues economically competitive.

6 Future Market Scenarios of Crop Residues for Power Generation

FASOMGHG is used to analyze market potential for biopower generated using crop residues. It is designed to simulate activity over a long period of time. In this paper, biopower production is simulated from the year 2000 to the year 2045 in five year intervals. Both cofire and fire-alone options are examined in the analyses. By incorporating various assumptions described above into FASOMGHG, the following scenarios are simulated over the period of 2000-2045:

1) Increase in coal prices
2) Increase in carbon dioxide (CO_2) equivalent prices
3) Changes in the heat content of crop residues
4) Changes in both the heat content and production costs of crop residues
5) Reduction in residue production costs
6) Improvement in crop yield
7) Improvement in conversion efficiency of residues

Under the first scenario, the impact of increase in coal prices on crop residue power production is explored. In the second scenario, various levels of CO_2 prices are employed to examine their effect on biopower production. Third scenario detects the impact of changes in the heat content of crop residues on biopower production. Fourth scenario examines the effect of changes in both the heat content and the production costs on biopower production. Fifth scenario studies how decreases in residue production costs alter biopower generation. Sixth scenario analyzes the impact of crop yield improvement on the use of residues for power generation. And the final scenario looks at how improvement in fuel conversion efficiency rate affects biopower production.

6.1 Coal Price Scenarios

By using alternative coal prices and constant CO_2 base price of zero in FASOMGHG, biopower production is simulated over time and results are shown in Table 18. The table shows that coal price has to be above \$40 per ton (equivalently \$2 per million Btu (MMBtu)) for wheat residues with cofire options to have market potential. It also shows that fire-alone option is not feasible for any crop residues unless coal price reaches above \$74.04 per ton (or \$3.7 per MMBtu). As coal price increases, more and more power plants switch to wheat residues with 20% cofire option. Corn, sorghum, barley, oats and rice residues do not have market potential in biopower production as coal price rises.

6.2 CO_2 Price Scenarios

A CO_2 equivalent price should ultimately reflect the future external cost of releasing GHG into the atmosphere. In the model, alternative CO_2 prices will be applied to CO_2, CH_4 (methane), and N_2O (nitrous oxide) emissions or offsets adjusted for their greenhouse gas or global warming potential (GWP)[16]. FASOMGHG is used to simulate future market scenarios for biopower production with chosen CO_2 equivalent prices ranging from \$0 to \$100 per ton. In this section, the coal price is assumed to be unchanged with the base price of \$24.68 per ton (or equivalently \$1.23 per MMBtu). Simulated results are reported in Table 19 which shows that an increase in CO_2 price is tremendously important for crop residues to have potential in power generation. The table indicates that the CO_2 price has to be about \$15 per ton for wheat residues with cofire options to have electricity production potential. Similar to coal price scenarios above, wheat residues with 20% cofire option will increasingly and significantly contribute to biopower production as CO_2 price increases from \$15 per ton to \$50 per ton. When the

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[16] The GWP compares the radiative forcing of the various GHGs relative to CO_2 over a given time period (Cole et al., 1996). The 100-year GWP for CO_2 equals 1. Higher values for CH_4 (21) and N_2O (310) reflect a greater heat trapping ability (see Schneider and McCarl, 2003).

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CO_2 price reaches \$100 per ton, biopower producers would be willing to primarily use wheat residues for power generation as wheat residues with fire-alone option have become feasible. At that level of CO_2 price, corn residues with fire-alone option would also become attractive to biopower producers as can be seen in the table.

6.3 Scenarios for Changes in the Heat Content

Wheat residues dominate most of the biopower production as coal and CO_2 prices increase (Tables 18 and 19). This is due to the fact that wheat residue has the heat content of 15.06 MMBtu per ton which is much higher than that of corn (about 9.23 MMBtu per ton) and other residues (see Table 3 for all the values of heat content). Changes in crop residue heat content can have great impact on the results of biopower production. In this section, biopower production results are obtained from simulating FASOMGHG, by assuming that all crop residues have the same heat content of 15.06 MMBtu per ton. The base price of coal is assumed to be constant, while CO_2 prices of \$0 to \$100 per ton are used in the simulation. Results are reported in Table 20 which shows that when all crop residues are assumed to have the same heat content, corn residues could potentially contribute to biopower generation in substantial amount as CO_2 price rises. When CO_2 price reaches above \$40 per ton, corn residues could surpass wheat residues in biopower production in both fire-alone and cofire options. Findings here suggest that crop residues with larger heat content are more likely to have market potential in biopower production than the residues with lower heat content.

6.4 Scenarios for Changes in Both the Heat Content and the Production Cost

In addition to assuming that all crop residues have the same heat content of 15.06 MMBtu per ton, this section allows all crop residues to have the same production cost of about \$30 per ton. Results (Table 21) indicate that when all crop residues are assumed to have the same heat content and production cost in the model, corn residues become dominant over wheat residues in biopower production as CO_2 price reaches about \$15 per ton or more. Based on these results (Table 20 & 21), we may conclude that for corn residues to become economically competitive with wheat residues they must have higher heat content. However, for them to become totally dominant over wheat residues in biopower production, they must also have lower production cost. Results also suggest that changes in the heat content will have a significantly greater impact on biopower production than changes in the production cost.

6.5 Scenarios for Production Cost Reductions

As mentioned above, reduction in the costs of bio-feedstock production is one of the important factors that make bio-feedstock economically competitive. Cost reductions can be accomplished by developing new and efficient technologies of harvesting, processing, and storage and transport systems. By employing various levels of cost reduction assumptions (i.e., 5% to 50% decrease in production costs) and of CO_2 prices, this section simulates the impact of cost reductions on biopower generation and answers the question of by how many percentage would decrease in residue production costs has to be achieved (with and without CO_2 prices) for biopower to have market potential. Results depicted in Figure 1 suggest that without any CO_2 price consideration; residue production costs must be reduced by at least 50% for crop residues to have any role in biopower production in the future.

With the CO_2 price of $5 per ton, biopower generation from crop residues will have market potential if the production costs are reduced by at least 25% (not reported for this case). But, when the CO_2 price reaches $10 per ton, Figure 1 indicates that cost reductions of 5% to 50% will induce biopower production. The figure clearly suggests that a higher percentage of residue cost reduction will induce power producers to generate more biopower from crop residues. A high percentage of cost reduction may not be as important when the CO_2 price rises to a significantly high level ($100 per ton or more), since at that high level of CO_2 price, power producers may be willing to pay more to acquire crop residues for electricity generation. In any case, increase in CO_2 prices will be quite important for crop residues to have any future role for electricity generation, as cost reduction will be difficult to achieve without drastic technological improvements.

6.6 Scenarios for Improvement in Crop Yield

Increase in the equivalent price of CO_2 would certainly make biopower more cost competitive and induce farmers to improve their crop yields through the adoption of new technologies. Improvement in crop yield could increase the availability of crop residues and hence bring down the residue price. This would give biopower producers more incentives to use crop residues for electricity generation. Using various levels of CO_2 prices, this section simulates the effect of improvement in crop yield on biopower production. The base price of coal is assumed to be constant. Two levels of yield improvement are simulated: an annual yield increase of 0.3% and of 0.6% respectively. Results described in Figure 2 suggest that improvement in crop yield alone would not be sufficient to boost biopower production. The CO_2 price will be an important factor in helping to induce biopower production. As indicated in the figure, even with yield improvement assumptions, the CO_2 price must increase to about \$15 per ton to encourage biopower producers to generate electricity from crop residues. From the figure, we may weakly conclude that higher crop yields could result in higher level of biopower production over time given that CO_2 prices are at a lower level, i.e. when CO_2 prices are below \$50 per ton. Overall results indicate that improvement in crop yield may not be an important factor in inducing more biopower production from crop residues.

6.7 Scenarios for Improvement in Fuel Conversion Efficiency

This section simulates the effect of power plant's fuel conversion efficiency improvement on biopower generation. Highly efficient power plants require less amount of Btu's fuel energy input to produce, say, a kilowatt hour (kWh) of electricity output. Increase in the fuel conversion efficiency will reduce the cost of fuel input. It is assumed in the simulation that improvement in the fuel conversion efficiency of power plants can be attained at an annual rate of 1% per year. Simulated results illustrated in Figure 3 suggest that without any significant increase in CO_2 prices, improvement in the efficiency of fuel conversion may not be enough to induce potentially a higher level of biopower production from crop residues. The figure shows that when the CO_2 price reaches at a substantially high level i.e., \$100 per ton or more, increase in the fuel conversion efficiency of power plants may be able to induce a higher level of biopower production.

6.8 Impact on Consumer and Producer Welfare

The impact of increase in CO_2 and coal prices on the welfare of U.S. consumers and producers is depicted in Figure 4[17]. The welfare is for agriculture only. The figure shows that as CO_2 price increases, agricultural producers' welfare also increases, but consumers suffer from welfare losses. This is because agricultural producers can gain credits from carbon sequestration as CO_2 price rises. Consumers' welfare declines due to the rise in agricultural commodity prices, the consequent of CO_2 price increase. The rise in coal prices has similar impact on the welfare of agricultural producers and consumers as indicated in the figure. But, this impact is relatively small compared to the impact of CO_2 price increase. Given different levels of CO_2 prices, Figure 5 shows that consumers' welfare rises as crop yield increases. This is to be expected as increase in crop yield will bring down the price of agricultural commodities. On the other hand, agricultural producers do not gain from crop yield increase as shown in the figure. For agricultural crop residues, increase in the heat content, improvement in the efficiency of biopower generation and reduction in the production cost bring little gains to the welfare of agricultural producers and consumers (not reported). This could suggest that biopower production from crop residues may not contribute much to the welfare of agricultural producers and consumers.

7 Summary and Conclusions

There are a number of factors which affect competitiveness of crop residues for power generation. These factors include changes in coal and CO_2 equivalent prices, changes in the heat content and the costs of residue production, and changes in crop yield and fuel conversion technology. Using FASOMGHG, scenarios for biopower production from crop residues are simulated and the key results of the paper can be summarized as follows.

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[17] The consumer and producer welfare data in the figure are based on the average of annual consumer and producer welfare from 2000 to 2045.

Under the alternative coal price scenarios, the price of coal has to be above $43 per ton for wheat residues with cofire options to have electricity production potential. Increase in coal prices induces more use of wheat residues as electricity producers switch to wheat residues with higher cofire options. Corn, sorghum, barley, oats and rice residues do not have much potential in generating biopower as coal price increases. Results also show that fire-alone option (100% firing with crop residues) is not feasible for any crop residues unless coal price surpasses well above $74.04 per ton.

Because coal is abundantly available in the U.S., scenarios for increase in coal prices do not appear to be realistic unless policy makers are willing to impose tax increase on coal production. As evidence of GHG emissions which cause global warming and climate change grows, global restrictions on GHG emissions have become tighter. Thus it appears that the external cost of carbon emissions (in the form of CO_2 equivalent prices in FASOMGHG) will likely rise in the near future.

Under the alternative CO_2 equivalent price scenarios, our simulation results show that the price of carbon or CO_2 has to be about $15 per ton for wheat residues with cofire options to have potential in electricity generation. Similar to the coal price scenarios, higher CO_2 equivalent prices encourage more use of wheat residues as electricity producers switch from lower residue cofire options to higher ones. Corn, sorghum, barley, oats and rice residues do not have potential in generating electricity when the CO_2 price is below $50 per ton. But when it reaches $100 per ton, corn and wheat residues with fire- alone options would become attractive to power generators. This is especially true for wheat residues, as at that level of carbon price wheat residues have become the main feedstock used in electricity generation.

It is interesting to see in our simulation results that corn residues, the most abundant residues in the U.S., do not account for much of the biopower production as CO_2 equivalent price increases. This is due to two factors: a) heat content and b) production costs of crop residues. Based on the literature and available data, this paper assumes that due to their higher moisture level, corn residues have lower heat content than wheat residues. In addition, we assume that the production costs of corn residues are higher than those of wheat residues. Changes in one or both of these two assumptions will have a significant impact on the production of biopower. Especially, changes in heat content may have a much greater impact on the biopower production than changes in production costs.

If we assume that all crop residues have the same heat content in the model, then results in this paper show that corn residues will become competitive with wheat residues and contribute to biopower production in tremendous amounts as CO_2 equivalent prices increase. In addition to the assumption of same heat content, if the assumption of same production costs is added into the model, then simulated results indicate that corn residues become the main contributor to biopower production, while wheat residues does not add much to the biopower generation as CO_2 prices rise. These results suggest that corn residues must have higher heat content and (less importantly) lower production costs in order for them to become competitive with wheat residues in biopower production.

The future of biopower production would likely depend on how carbon price evolves over time. The analysis in this paper shows that without any consideration of CO_2 equivalent price (i.e. when the CO_2 price is zero), crop residue production costs must be reduced by at least 50 percent to induce biopower production. Rising CO_2 prices together with falling residue production costs will undoubtedly bring biopower production to a significantly high level. But given the current situation, cost reductions of 50 percent will not be easy to achieve without drastic improvements in residue production technologies and developments in bio-feedstock markets. The future of biopower production from crop residues could depend on the price of CO_2 emission reductions. Higher carbon prices would likely encourage more biopower production.

In order to induce biopower producers to use crop residues without having them to worry about reductions in residue production costs, this paper shows that the price of CO_2 has to reach above \$10 per ton. In addition, the paper shows that improvements in crop yield do not have much impact on biopower production. However, the energy recovery efficiency does have significant positive impact on the biopower desirability only if the carbon equivalent price rises substantially.

Based on all the simulation results under various alternative scenarios as described above, the following conclusions can be made about crop residue biopower production.

- Due to their low heat content and high transaction costs, crop residues cost much more than coal and are not used in electricity generation under base conditions.
- For crop residues to become competitive with coal, their costs of production must be cut by more than half or effective costs of using coal must rise.
- For crop residues to have a future role in biopower production in the form of cofiring, either the price of coal has to increase to well above $2 per million Btu ($40 per ton) or the price of carbon must rise to at least $15 per ton. The use of power plants fueled entirely by crop residues is unlikely happen, unless either the coal price or the price of carbon or both rise substantially.
- When carbon prices are high, wheat residues dominate since they have higher heat content than other crop residues.
- Delivered costs of crop residues are lower with cofire options than with fire-alone options and cofired options dominate at lower carbon prices.

Overall results suggest that the feasibility of using crop residues for power production will depend on the increase in the future price of carbon emissions or coal and if we wish to reduce emissions this would be a way of accomplishing that.

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Table 1. Percent of Net Electricity Generation by Different Fuel Sources, 1990 and 2005

Fuel Type\Year	1990 (%)	2005 (%)
Coal	52.65	50.04
Natural Gas	12.31	18.67
Nuclear	19.05	19.39
Petroleum	4.18	3.03
Hydro	9.67	6.59
Biomass[18]	1.51	1.54
Geothermal	0.51	0.38
Solar	0.01	0.01
Wind	0.09	0.36

Source: Annual Energy Review Database (Energy Information Administration)

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[18] Biomass includes wood, wood waste, sludge waste, black liquor, municipal solid waste, landfill gas, tires, agricultural byproducts and other biomass.

Table 2. Straw to Grain Ratio, Weight and Moisture Content of Six Crops

Crop	Straw to Grain Ratio	Grain Weight (Pounds/bushel)	Moisture Content (%)
Corn	1.0 : 1	56	12.0
Wheat	1.5 : 1	60	8.9
Barley	1.5 : 1	48	10.3
Oats	1.0 : 1	32	10.3
Sorghum	1.0 : 1	56	10.0
Rice	1.0 : 1	45	15.0

Table 3. Heat Content for Crop Residues

Crop Residues	Heat Content (Million Btu/ton)
Corn stover	9.23
Wheat straw	15.06
Barley straw	14.88
Oat straw	14.88
Rice straw	13.07
Sorghum stalk	13.24

Table 4. Definitions of 11 Regions in FASOMGHG

Key	Region	States/Subregions
NE	Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia
LS	Lake States	Michigan, Minnesota, Wisconsin
CB	Corn Belt	All regions in Illinois, Indiana, Iowa, Missouri, Ohio
GP	Great Plains	Kansas, Nebraska, North Dakota, South Dakota
SE	Southeast	Virginia, North Carolina, South Carolina, Georgia, Florida
SC	South Central	Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Eastern Oklahoma, Tennessee, Eastern Texas
SW	Southwest	Western and Central Oklahoma, All of Texas but the Eastern Part – Texas High Plains, Texas Rolling Plains, Texas Central Blacklands, Texas Edwards Plateau, Texas Coastal Bend, Texas South, Texas Trans Pecos
RM	Rocky Mountains	Arizona, Colorado, Idaho, Montana, Eastern Oregon, Nevada, New Mexico, Utah, Eastern Washington, Wyoming
PSW	Pacific Southwest	All regions in California
PNWE	Pacific Northwest – East side	Oregon and Washington, east of the Cascade mountain range
PNWW	Pacific Northwest – West side	Oregon and Washington, west of the Cascade mountain range

Table 5. Weighted Average Yield of Removable Crop Residues (in Tons/acre)

Region	Corn	Wheat	Sorghum	Barley	Oats	Rice
NE	1.30	1.08	1.11	0.61	0.36	-
LS	1.52	0.64	-	0.42	0.34	-
CB	1.85	1.16	1.11	0.63	0.47	0.20
GP	1.59	0.58	0.93	0.43	0.35	-
SE	1.37	0.87	0.76	0.58	0.33	-
SC	1.61	0.86	1.05	0.64	0.26	0.40
SW	1.27	0.49	0.52	0.30	0.19	0.41
RM	1.59	0.53	0.53	0.56	0.33	-
PSW	1.67	0.82	0.48	0.40	0.31	0.59
PNWE	1.86	0.42	-	0.45	0.38	-

Table 6. Total Harvested Acres (in Million Acres)

Region	Corn	Wheat	Sorghum	Barley	Oats	Rice
NE	2.35	0.55	0.01	0.17	0.22	-
LS	10.70	2.49	-	0.19	0.46	-
CB	33.69	2.78	0.30	-	0.28	0.21
GP	14.91	20.92	4.33	1.54	0.47	-
SE	1.44	1.04	0.05	0.07	0.09	-
SC	2.77	2.14	0.52	0.01	0.00	2.43
SW	1.59	6.89	3.00	-	0.17	0.20
RM	1.27	8.00	0.37	1.66	0.15	-
PSW	0.16	0.46	-	0.11	0.03	0.47
PNWE	0.07	3.21	-	0.52	0.04	-

Table 7. Total Removable Crop Residues (in Million Tons)

Region	Corn	Wheat	Sorghum	Barley	Oats	Rice	Total
NE	3.07	0.59	0.01	0.10	0.08	-	3.86
LS	16.21	1.58	-	0.08	0.15	-	18.03
CB	62.19	3.23	0.33	-	0.13	0.04	65.92
GP	23.65	12.16	4.03	0.66	0.16	-	40.66
SE	1.98	0.90	0.03	0.04	0.03	-	2.98
SC	4.46	1.84	0.55	0.01	0.00	0.98	7.83
SW	2.03	3.36	1.55	-	0.03	0.08	7.06
RM	2.03	4.23	0.19	0.93	0.05	-	7.43
PSW	0.27	0.38	-	0.04	0.01	0.28	0.97
PNWE	0.14	1.35	-	0.23	0.01	-	1.73
Total	116.02	29.62	6.70	2.09	0.66	1.38	156.47

Table 8. Weighted Average Crop Residue Density (in %)

Region	Corn	Wheat	Sorghum	Barley	Oats	Rice
NE	3.29	0.42	0.34	1.48	1.42	-
LS	7.36	1.21	-	0.08	0.27	-
CB	20.82	2.12	0.27	-	0.15	0.08
GP	9.38	12.68	5.43	2.26	0.24	-
SE	0.93	0.61	0.07	0.07	0.05	-
SC	1.61	1.11	0.20	-	-	2.23
SW	0.65	4.35	1.61	-	0.07	0.50
RM	0.51	2.08	0.08	0.46	0.03	-
PSW	0.09	0.17	0.19	0.09	0.03	0.10
PNWE	0.01	1.33	-	0.25	0.01	-

Table 9. Average Hauling Distance for Corn Residues (in Miles)

Region	Cofire5%	Cofire10%	Cofire15%	Cofire20%	Fire100%
NE	13.12	18.38	22.72	26.47	78.39
LS	8.13	11.40	14.09	16.41	48.60
CB	4.38	6.14	7.59	8.84	26.18
GP	7.04	9.86	12.19	14.20	42.06
SE	24.02	33.66	41.60	48.46	143.52
SC	16.87	23.65	29.23	34.05	100.84
SW	29.89	41.89	51.76	60.30	178.60
RM	30.14	42.24	52.20	60.81	180.10
PSW	70.08	98.23	121.39	141.42	418.84
PNWE	199.41	279.48	345.39	402.36	-

Table 10. Average Hauling Distance for Wheat Residues (in Miles)

Region	Cofire5%	Cofire10%	Cofire15%	Cofire20%	Fire100%
NE	31.47	44.10	54.50	63.49	188.05
LS	24.27	34.02	42.04	48.98	145.06
CB	13.53	18.97	23.44	27.31	80.88
GP	7.83	10.98	13.57	15.81	46.81
SE	29.15	40.86	50.50	58.83	174.23
SC	21.68	30.38	37.55	43.74	129.55
SW	14.59	20.45	25.27	29.44	87.20
RM	20.25	28.38	35.08	40.86	121.03
PSW	56.55	79.26	97.95	114.10	337.95
PNWE	28.42	39.83	49.22	57.34	169.82

Table 11. Average Hauling Cost for Corn Residues (in Dollars/ton)

Region	Cofire5%	Cofire10%	Cofire15%	Cofire20%	Fire100%
NE	7.39	8.54	9.50	10.32	21.74
LS	6.29	7.01	7.60	8.11	15.19
CB	5.46	5.85	6.17	6.44	10.26
GP	6.05	6.67	7.18	7.62	13.75
SE	9.78	11.90	13.65	15.16	36.07
SC	8.21	9.70	10.93	11.99	26.68
SW	11.07	13.71	15.89	17.77	43.79
RM	11.13	13.79	15.98	17.88	44.12
PSW	19.92	26.11	31.21	35.61	96.64
PNWE	48.37	65.99	80.49	93.02	-

Table 12. Average Hauling Cost for Wheat Residues (in Dollars/ton)

Region	Cofire5%	Cofire10%	Cofire15%	Cofire20%	Fire100%
NE	11.42	14.20	16.49	18.47	45.87
LS	9.84	11.98	13.75	15.27	36.41
CB	7.48	8.67	9.66	10.51	22.29
GP	6.22	6.92	7.48	7.98	14.80
SE	10.91	13.49	15.61	17.44	42.83
SC	9.27	11.18	12.76	14.12	33.00
SW	7.71	9.00	10.06	10.98	23.68
RM	8.96	10.74	12.22	13.49	31.13
PSW	16.94	21.94	26.05	29.60	78.85
PNWE	10.75	13.26	15.33	17.11	41.86

Table 13. Average Delivered Cost Estimates of Corn Residues (in Dollars/ton)

Region	Cofire5%	Cofire10%	Cofire15%	Cofire20%	Fire100%
NE	46.83	47.99	48.94	49.77	61.19
LS	45.73	46.45	47.04	47.56	54.64
CB	44.91	45.30	45.62	45.89	49.71
GP	45.49	46.12	46.63	47.07	53.20
SE	49.23	51.35	53.10	54.61	75.52
SC	47.66	49.15	50.38	51.44	66.13
SW	50.52	53.16	55.33	57.21	83.24
RM	50.58	53.24	55.43	57.32	83.57
PSW	59.36	65.56	70.65	75.06	136.09
PNWE	87.82	105.43	119.93	132.47	-

Table 14. Average Delivered Cost Estimates of Wheat Residues (in Dollars/ton)

Region	Cofire5%	Cofire10%	Cofire15%	Cofire20%	Fire100%
NE	45.38	48.16	50.45	52.43	79.83
LS	43.80	45.94	47.71	49.23	70.37
CB	41.44	42.63	43.62	44.47	56.25
GP	40.18	40.87	41.44	41.94	48.76
SE	44.87	47.45	49.57	51.40	76.79
SC	43.23	45.14	46.72	48.08	66.96
SW	41.67	42.96	44.02	44.94	57.64
RM	42.91	44.70	46.18	47.45	65.09
PSW	50.90	55.90	60.01	63.56	112.81
PNWE	44.71	47.22	49.29	51.07	75.82

Table 15. Average Cost of Coal Delivered to Electric Utilities (in Dollars/MMBtu)

Region	1998	2001	2004	2005
NE	1.65	1.63	1.78	2.15
LS	1.14	1.08	1.16	1.28
CB	1.22	1.15	1.18	1.32
GP	0.61	0.63	0.68	0.73
SE	1.80	1.96	2.27	2.71
SC	1.37	1.29	1.51	1.75
SW	0.88	0.96	1.06	1.04
RM	1.01	1.02	1.07	1.14
Pacific	1.12	0.95	1.00	1.07

Source: Data are derived from Energy Information Administration.

Table 16. Average Delivered Cost Estimates of Corn Residues (in Dollars/MMBtu)

Region	Cofire5%	Cofire10%	Cofire15%	Cofire20%	Fire100%
NE	5.08	5.20	5.30	5.39	6.63
LS	4.96	5.03	5.10	5.15	5.92
CB	4.87	4.91	4.94	4.97	5.39
GP	4.93	5.00	5.05	5.10	5.77
SE	5.34	5.57	5.76	5.92	8.19
SC	5.17	5.33	5.46	5.58	7.17
SW	5.48	5.76	6.00	6.20	9.02
RM	5.48	5.77	6.01	6.21	9.06
PSW	6.43	7.11	7.66	8.14	14.75
PNWE	9.52	11.43	13.00	14.36	-

Table 17. Average Delivered Cost Estimates of Wheat Residues (in Dollars/MMBtu)

Region	Cofire5%	Cofire10%	Cofire15%	Cofire20%	Fire100%
NE	3.01	3.20	3.35	3.48	5.30
LS	2.91	3.05	3.17	3.27	4.67
CB	2.75	2.83	2.90	2.95	3.74
GP	2.67	2.71	2.75	2.79	3.24
SE	2.98	3.15	3.29	3.41	5.10
SC	2.87	3.00	3.10	3.19	4.45
SW	2.77	2.85	2.92	2.98	3.83
RM	2.85	2.97	3.07	3.15	4.32
PSW	3.38	3.71	3.99	4.22	7.49
PNWE	2.97	3.14	3.27	3.39	5.04

Table 18. Biopower Production Over Time under Alternative Coal Prices (in Number of 100MW Plants)

Coal Price	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
Coal $43.19										
Wheat (Cofire 5%, 10% and 15%)	-	2	10	11	16	23	26	32	19	26
Coal $49.36										
Wheat (Cofire 5%, 10% and 15%)	2	8	4	19	26	39	41	47	51	63
Wheat (Cofire 20%)	1	1	14	1	2	2	3	3	4	5
Coal $61.70										
Wheat (Cofire 10% and 15%)	-	-	2	4	6	14	32	36	75	84
Wheat (Cofire 20%)	2	12	19	27	38	44	29	29	17	29
Barley (Cofire 10%)	-	-	-	-	-	-	-	-	4	5
Coal $67.87										
Wheat (Cofire 10% and 15%)	-	-	3	7	8	6	14	14	13	23
Wheat (Cofire 20%)	2	12	19	27	36	51	47	51	93	97
Barley (Cofire 10%)	-	-	-	-	-	-	-	-	4	5
Coal $74.04										
Wheat (Cofire 15%)	-	-	-	4	8	6	6	9	-	-
Wheat (Cofire 20%)	2	12	24	31	35	51	55	56	107	123
Barley (Cofire 10%)	-	-	-	-	-	-	-	1	-	-

Table 19. Bioelectricity Production Over Time under Alternative Carbon Prices (in Number of 100MW Plants)

Carbon Price	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
CO2 $10										
Wheat (Cofire 5% and 10%)	-	-	4	-	-	1	1	2	2	3
CO2 $15										
Wheat (Cofire 5%, 10% and 15%)	3	6	13	12	20	33	35	38	43	54
Wheat (Cofire 20%)	-	-	1	1	2	2	3	3	4	5
CO2 $30										
Wheat (Cofire 10% and 15%)	-	-	3	7	10	6	13	14	48	53
Wheat (Cofire 20%)	10	12	19	27	32	51	47	51	42	70
Barley (Cofire 10%)	-	-	-	-	-	-	-	-	4	5
CO2 $40										
Wheat (Cofire 15%)	-	-	-	-	-	-	6	7	-	-
Wheat (Cofire 20%)	10	12	24	35	46	57	53	57	107	128
Barley (Cofire 15% and 20%)	-	-	-	-	-	-	1	-	1	-
CO2 $50										
Corn (Cofire 20%)	-	-	-	-	-	-	5	-	-	-
Wheat (Cofire 15%)	-	-	-	-	-	-	3	-	-	-
Wheat (Cofire 20%)	12	13	24	35	43	61	60	68	109	127
Wheat (Fire-alone100%)	1	4	5	7	9	11	14	17	-	-
Barley (Cofire 15% and 20%)	-	-	-	-	-	-	1	-	1	-
Rice (Cofire 20%)	-	-	-	-	-	-	1	-	-	-

Table 19. (Continued)

Carbon Price	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
CO2 $100										
Corn (Cofire 20%)	-	-	-	-	2	2	5	6	-	-
Corn (Fire-alone100%)	-	-	-	-	-	-	-	64	156	203
Sorghum (Fire-alone100%)	-	-	-	-	-	-	-	-	4	-
Wheat (Cofire 20%)	-	-	3	5	6	10	10	13	29	18
Wheat (Fire-alone100%)	11	13	25	29	43	66	69	77	81	110
Barley (Cofire 20%)	-	-	-	-	-	1	1	5	-	1
Rice (Cofire 20%)	-	-	-	-	-	-	-	1	3	-

Table 20. Biopower Production Over Time under Alternative Carbon Prices with the Assumption that All Crop Residues have the Same Heat Content (in Number of 100MW Plants)

Carbon Price	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
CO2 $10										
Wheat (Cofire 5% and 10%)	-	-	4	-	-	1	1	2	2	3
CO2 $15										
Corn (Cofire 5%, 10% and 15%)	1	1	3	2	11	21	10	11	34	30
Wheat (Cofire 5%, 10% and 15%)	2	5	11	10	13	29	35	38	44	54
Wheat (Cofire 20%)	-	-	1	1	2	2	3	3	4	5
CO2 $30										
Corn (Cofire 15%)	-	-	-	-	-	-	-	2	-	-
Corn (Cofire 20%)	8	10	16	28	36	28	34	39	60	56
Wheat (Cofire 10% and 15%)	-	-	3	7	10	6	7	9	48	55
Wheat (Cofire 20%)	2	2	3	4	12	35	38	41	24	41
Barley (Cofire 10% and 15%)	-	-	-	-	-	-	-	-	4	5
Rice (Cofire 15%)	-	-	-	-	-	1	1	1	3	3
CO2 $40										
Corn (Cofire 20%)	8	10	22	37	36	53	35	40	63	57
Wheat (Cofire 15%)	-	-	-	-	-	-	6	-	-	-
Wheat (Cofire 20%)	2	2	7	12	27	19	39	48	86	106
Barley (Cofire 20%)	-	-	-	-	-	-	-	-	1	-
Rice (Cofire 20%)	-	-	1	1	1	1	1	1	3	3

Table 20. (Continued)

Carbon Price	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
CO2 $50										
Corn (Cofire 20%)	2	2	8	21	15	21	13	15	53	41
Corn (Fire-alone 100%)	40	40	82	92	141	162	224	241	242	272
Wheat (Cofire 15%)	-	-	-	-	-	-	6	-	-	-
Wheat (Cofire 20%)	4	3	7	11	19	24	21	30	77	89
Wheat (Fire-alone 100%)	1	4	5	7	9	11	14	17	4	6
Barley (Cofire 15% and 20%)	-	-	-	-	-	-	1	-	1	1
Rice (Cofire 20%)	-	-	1	1	1	1	1	1	4	4
CO2 $100										
Corn (Cofire 20%)	-	-	-	1	4	6	9	18	-	-
Corn (Fire-alone 100%)	52	53	82	117	151	189	230	249	357	347
Wheat (Cofire 20%)	-	-	3	4	8	10	10	15	37	36
Wheat (Fire-alone 100%)	10	10	12	16	34	46	53	59	69	80
Barley (Cofire 20%)	-	-	-	-	-	1	1	3	-	2
Rice (Cofire 20%)	-	-	-	1	1	1	1	1	4	-
Rice (Fire-alone 100%)	-	-	-	-	-	-	-	-	-	2

Table 21. Biopower Production Over Time under Alternative Carbon Prices with the Assumption that All Crop Residues have the Same Heat Content and Production Cost (in Number of 100MW Plants)

Carbon Price	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
CO2 $15										
Corn (Cofire 5%, 10% and 15%)	1	5	3	16	29	49	44	48	44	55
Corn (Cofire 20%)	-	-	13	-	-	-	-	-	-	-
Wheat (Cofire 5%)	-	-	-	-	-	-	-	-	2	3
CO2 $30										
Corn (Cofire 15%)	-	-	-	-	-	-	-	2	-	-
Corn (Cofire 20%)	8	10	17	27	43	51	59	65	73	85
Wheat (Cofire 15%)	-	-	-	-	-	1	1	2	39	42
Wheat (Cofire 20%)	1	1	2	3	3	9	13	15	10	12
Rice (Cofire 15%)	-	-	1	1	1	1	1	1	3	4
CO2 $40										
Corn (Cofire 20%)	8	10	21	36	45	54	60	66	95	86
Wheat (Cofire 15%)	-	-	-	-	-	-	6	6	-	-
Wheat (Cofire 20%)	1	1	2	3	3	9	14	17	45	65
Barley (Cofire 20%)	-	-	-	-	-	-	-	-	1	-
Rice (Cofire 20%)	-	-	1	1	1	1	1	1	3	4

Table 21. (Continued)

Carbon Price	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
CO2 $50										
Corn (Cofire 20%)	3	3	8	22	18	27	20	15	80	56
Corn (Fire-alone100%)	40	40	87	92	138	173	238	258	245	279
Wheat (Cofire 15%)	-	-	-	-	-	-	6	-	-	-
Wheat (Cofire 20%)	1	1	2	3	3	11	14	23	42	65
Barley (Cofire 15% and 20%)	-	-	-	-	-	-	1	-	1	-
Rice (Cofire 20%)	-	-	1	1	1	1	1	1	4	4
CO2 $100										
Corn (Cofire 20%)	-	-	-	1	4	7	9	18	-	-
Corn (Fire-alone100%)	56	57	87	124	160	200	244	266	369	371
Sorghum (Cofire 20%)	-	-	-	-	-	-	-	-	1	-
Wheat (Cofire 20%)	1	1	1	6	6	9	10	14	33	42
Wheat (Fire-alone100%)	-	-	6	6	11	35	37	42	56	49
Barley (Cofire 20%)	-	-	-	-	-	-	-	1	-	1
Rice (Cofire 20%)	-	-	-	1	1	1	1	1	4	-

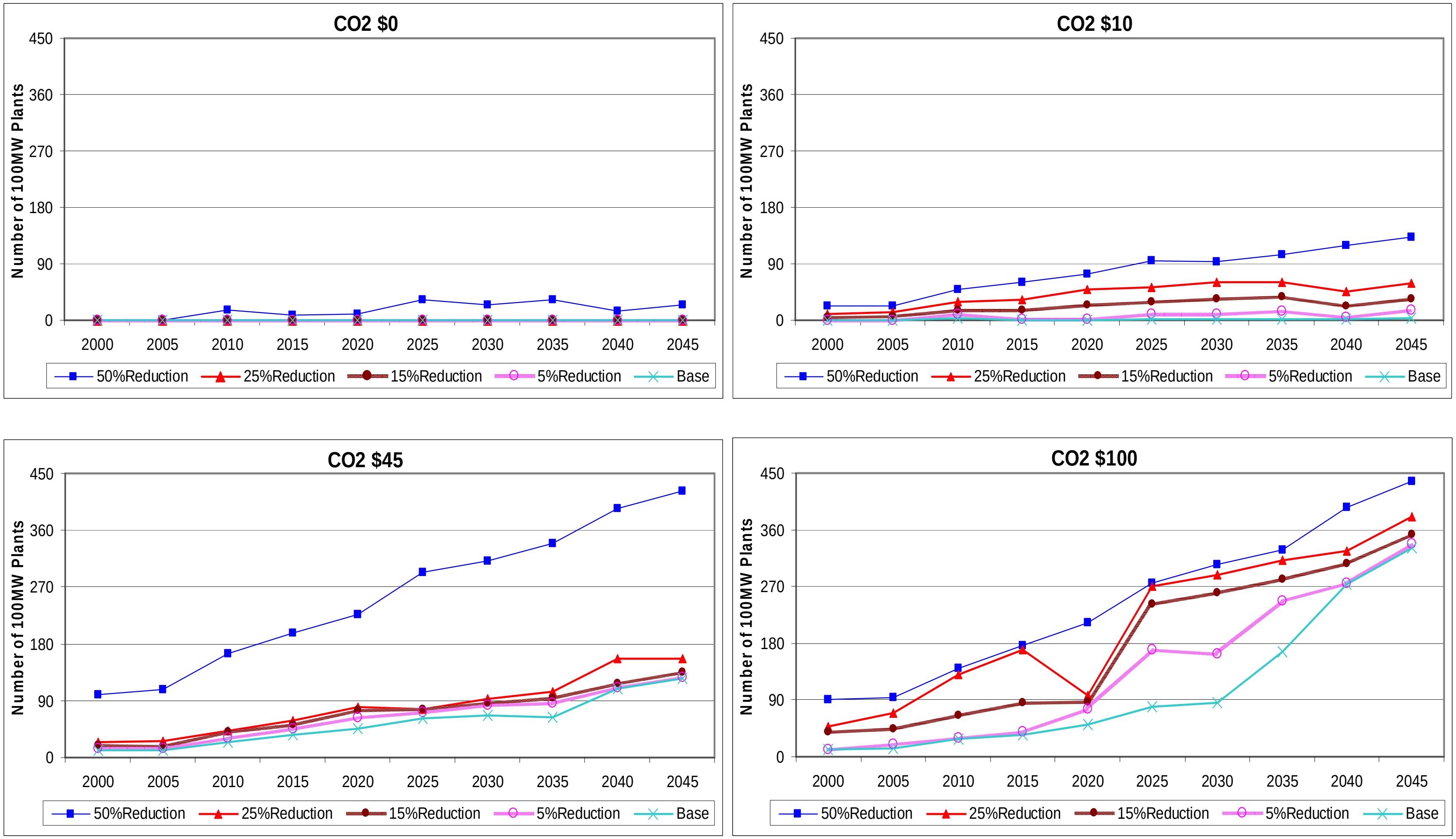


Figure 1. Total Biopower Production (in Number of 100MW Plants) for Cost Reduction Scenarios

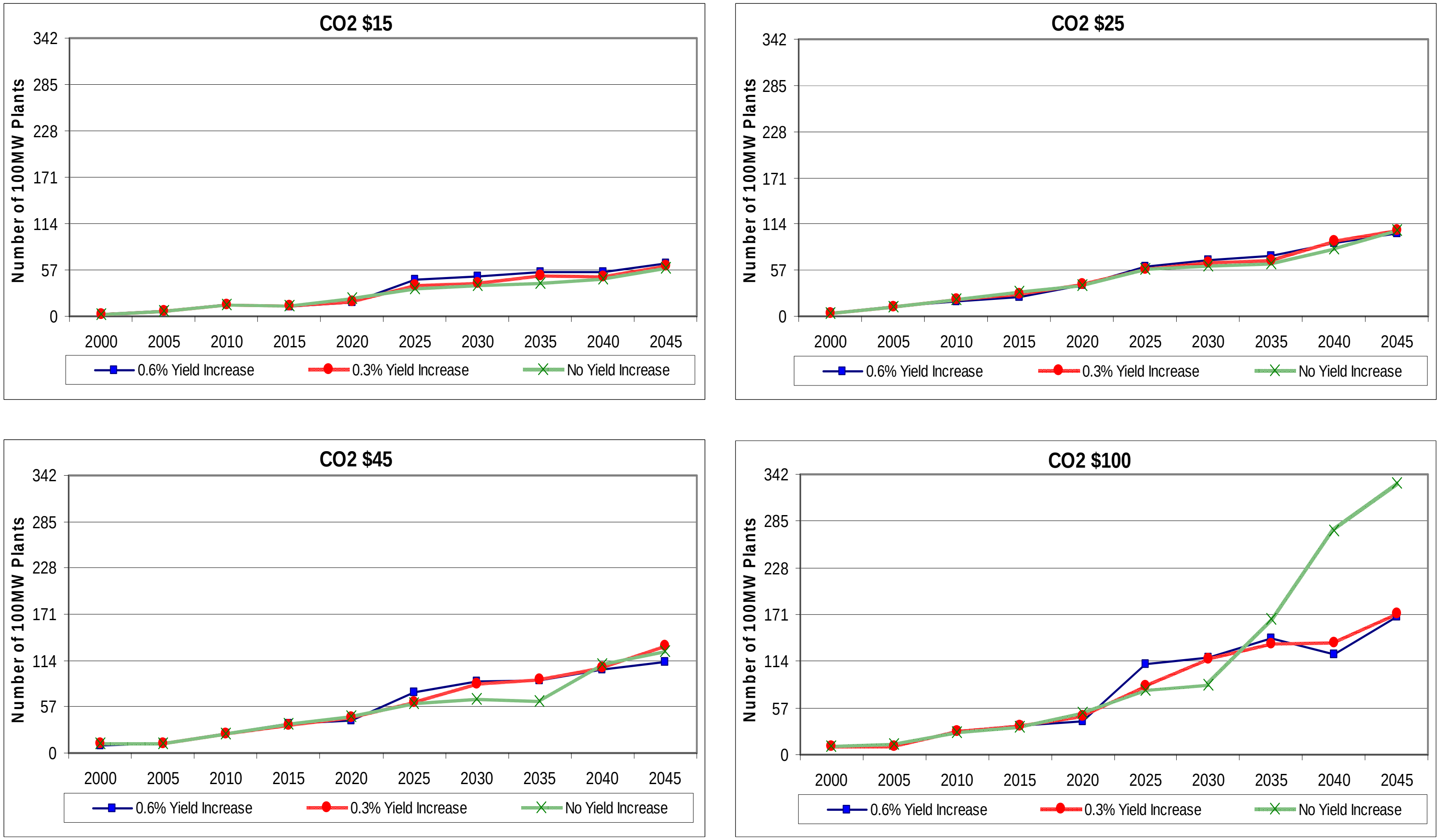


Figure 2. Total Biopower Production (in Number of 100MW Plants) for Yield Improvement Scenarios

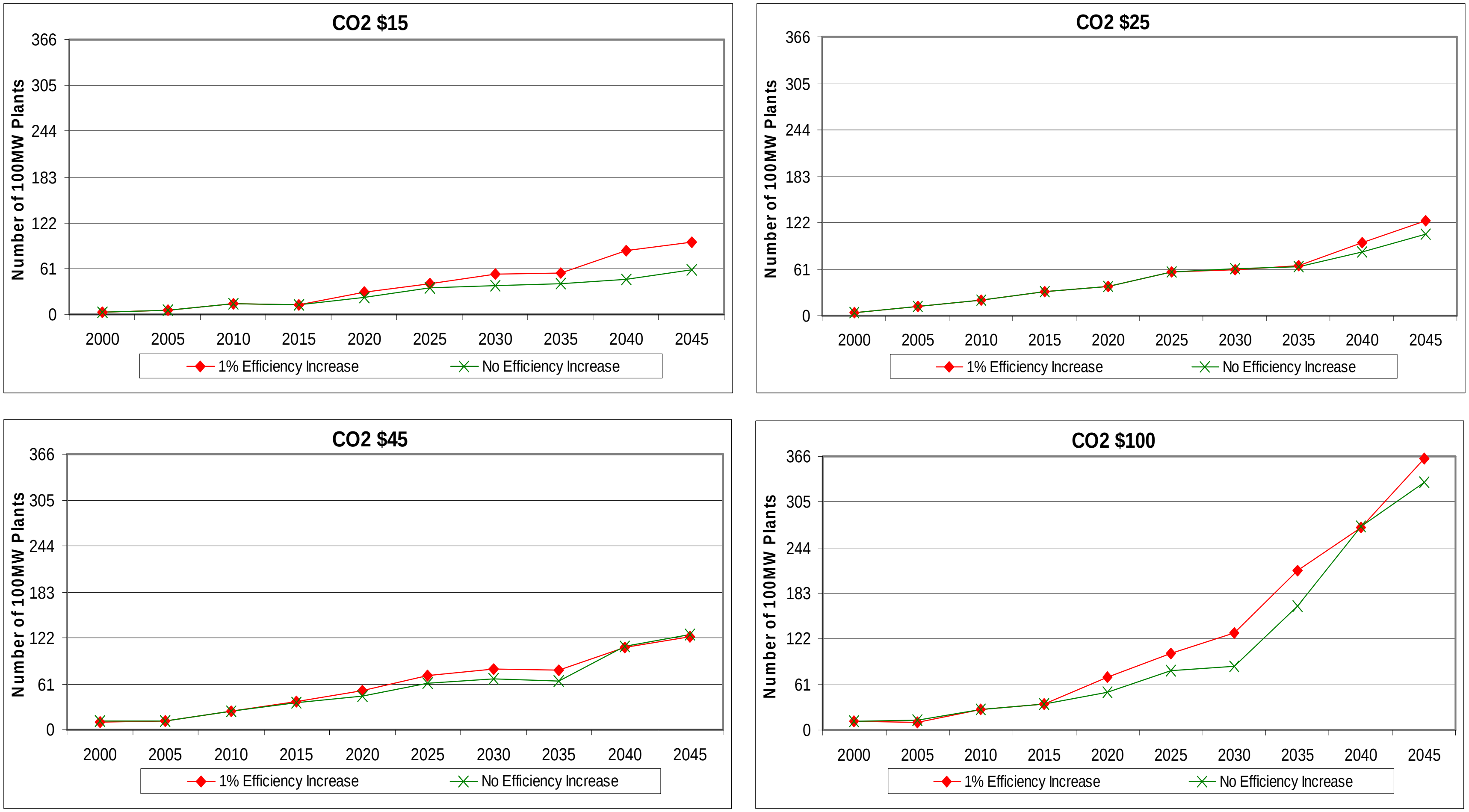
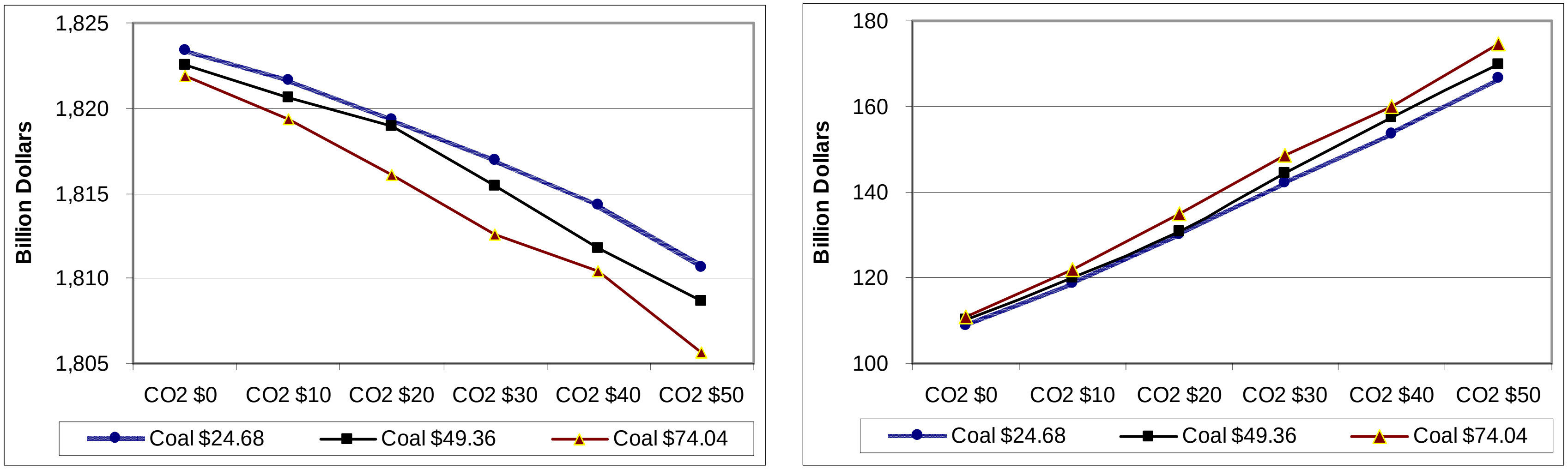


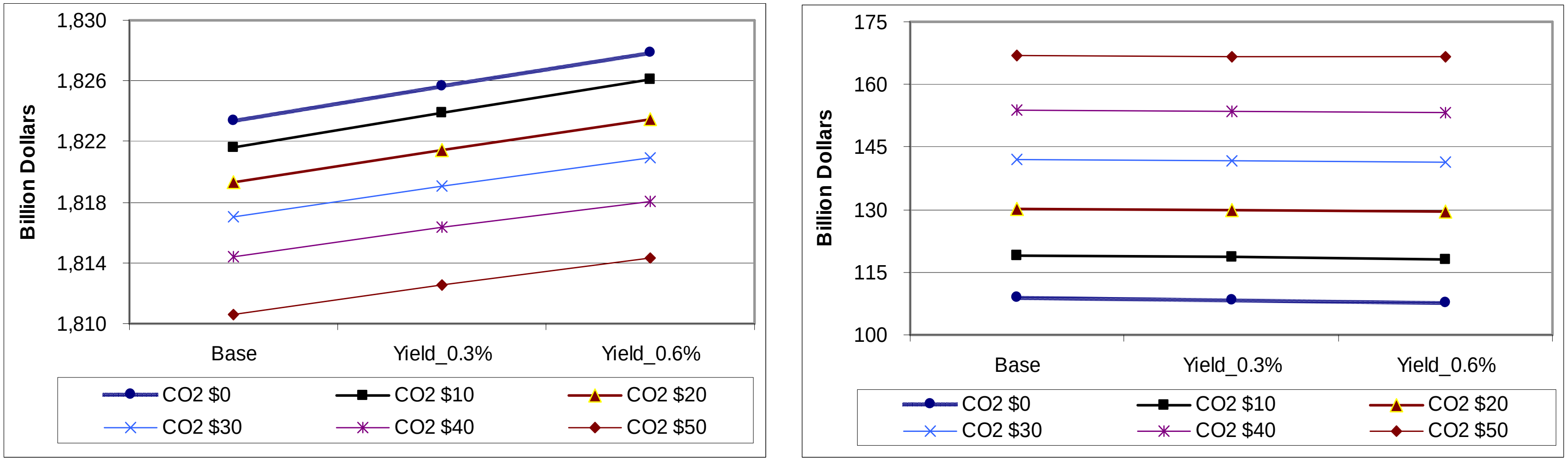
Figure 3. Total Biopower Production (in Number of 100MW Plants) for Power Plant Fuel Efficiency Improvement Scenarios



Consumer Welfare

Producer welfare

Figure 4. Impact of Changes in Coal and Carbon Prices on Consumer and Producer Welfare



Consumer Welfare

Producer welfare

Figure 5. Impact of Changes in Yield Improvements on Consumer and Producer Welfare