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A comparative analysis of woody biomass and coal for electricity generation under various CO_2 emission reductions and taxes

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Abstract

Mitigating global climate change via CO_2 emission control and taxation is likely to enhance the economic potential of bioenergy production and utilization. This study investigated the cost competitiveness of woody biomass for electricity production in the US under alternative CO_2 emission reductions and taxes. We first simulated changes in the price of coal for electricity production due to CO_2 emission reductions and taxation using a computable general equilibrium model. Then, the costs of electricity generation fueled by energy crops (hybrid poplar), logging residues, and coal were estimated using the capital budgeting method. Our results indicate that logging residues would be competitive with coal if emissions were taxed at about US\$25 Mg^{-1} CO_2, while an emission tax US\$100 Mg^{-1} CO_2 or higher would be needed for hybrid poplar plantations at a yield of 11.21 dry Mg ha^{-1} yr^{-1} (5 dry tons ac^{-1} yr^{-1}) to compete with coal in electricity production. Reaching the CO_2 emission targets committed under the Kyoto Protocol would only slightly increase the price of fossil fuels, generating little impact on the competitiveness of woody biomass. However, the price of coal used for electricity production would significantly increase if global CO_2 emissions were curtailed by 20% or more. Logging residues would become a competitive fuel source for electricity production if current global CO_2 emissions were cut by 20–30%. Hybrid poplar plantations would not be able to compete with coal until emissions were reduced by 40% or more.

Keywords: Woody biomass; Coal; Electricity production; CO_2 emissions and taxes; Computable general equilibrium modeling

1. Introduction

Market expansion of woody biomass energy in the United States has long been hindered by its high production cost relative to fossil fuels, even though the former is more environmentally benign than the latter. However, due to increasing atmospheric greenhouse gas concentration, global climate is predicted to change at an unprecedented rate [1]. Combustion of fossil fuels is a major source of greenhouse gas emissions. To reduce greenhouse gas emissions from energy consumption, several policy alternatives such as emission taxes and tradable emission permits have been proposed. These mitigation policies are likely to enhance the competitive advantage of woody biomass energy over fossil fuels as the former can displace CO_2 emissions from the latter [2,3]. Yet, limited literature is available on the effect of CO_2 emission reductions and taxes on the economic potential or cost competitiveness of woody biomass energy in the United States.

Though economic analysis of biomass energy production in the US has been extensive [4], many existing studies were primarily based on research trial plantations, focused on biomass feedstock production, and did not account for environmental benefits [5–8]. According to these earlier studies, biomass production costs vary across regions and crops and are affected by yield. Generalization of these empirical studies has also led to the development of models to estimate biomass production costs under different circumstances. One of these models is the Oak Ridge National Laboratory (ORNL) model capable of estimating the full economic cost of biomass production in eight US

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regions [9]. Recently several studies have explored the technical and economic feasibility of producing energy wood from logging and thinning residues [10–12]. Various integrated harvesting systems, which simultaneously harvest conventional wood products and biomass for energy, have been developed and tested in several countries [13–15]. The estimated marginal costs of recovering energy wood using integrated harvesting systems show great potential for utilizing logging residues in energy production [16].

Economic analysis beyond biomass feedstock production, though limited, has also gained momentum recently. Biomass cofiring with coal in electricity production has been demonstrated to be technically feasible and, in some cases, cost effective as well [17]. In general, generating electricity using biomass is still in its infancy, and economic competitiveness remains the major barrier [18,19]. However, most of the existing studies focus on traditional internal (private) production costs and benefits. Externalities in energy production and consumption are evident and different from one type of energy to another. Some externalities represent additional costs to society. Incorporating social costs like CO_2 emissions into the economic evaluation of bioenergy production and consumption will enrich the existing body of knowledge and provide a more comprehensive picture about the cost competitiveness of biomass energy.

To this end, we conducted a comparative economic analysis of woody biomass and coal in terms of both feedstock and electricity production under different CO_2 emission reduction and tax scenarios. Both short-rotation woody biomass and logging residues from conventional forests were examined and compared with coal. Instead of adding the cost of carbon emissions directly to existing energy prices, we simulated market equilibrium energy prices at different CO_2 emission tax rates and emission reduction levels under a general equilibrium framework. This approach enabled us to avoid determining a carbon price, which varies tremendously and is very difficult, if not impossible, to predict. Also, the simulated prices can better reflect real market conditions and greenhouse gas emission mitigation policy because in our simulation model, energy substitutions, emission trading, and intersectoral and interregional linkages are accounted for. In the next section, the methods used in this analysis will be described. Then, results will be presented and discussed, followed by conclusions.

2. Methods

2.1. The simulation model and scenarios

Changes in energy prices resulting from CO_2 emission reductions and taxes were projected using a computable general equilibrium (CGE) model. CGE models are based on microeconomic, neoclassical theory, while being able to incorporate structural rigidities intended to capture non-neoclassical behavior, macroeconomic imbalance, and institutional rigidities. Since the pioneer work in applied CGE modeling by Johansen [20], the CGE modeling approach has been further developed and applied to a wide range of economic studies [21–24]. With improvements in theory and modeling capacity, the CGE modeling approach has become a powerful methodological tool for policy analysis, particularly when multisectoral and multiregional linkages are important. CGE models permit economists to analyze both intrasectoral and intersectoral impacts of policy actions and other exogenous events in the context of a consistent and interrelated global economy. Because energy is virtually an input factor for all economic sectors and is extensively traded internationally, changes in energy prices are the result of interactions among many sectors and regions. This makes the CGE approach an effective and appropriate tool for analyzing the effect of CO_2 emission reductions and taxes on energy prices.

The CGE model used in this study is based on the Global Trade Analysis Project (GTAP) model, which was initially constructed to analyze the economic effect of trade policy [25]. The standard GTAP model is a comparative static, multisectoral, and multiregional model. It assumes constant returns to scale in all production sectors and perfect competition in all markets. Products are differentiated by country of origin using the traditional Armington approach [26], which assumes that products from different countries are not perfect substitutes. For each region in the model, expenditures by private households and the government and savings are determined by maximizing an aggregate Cobb–Douglas utility function within a budget constraint. On the production side, the households sell endowment commodities to firms. Then, the profit-maximizing firms use these endowment commodities along with intermediate goods to produce final goods and services. The government finances its expenditures by imposing taxes on the private households, firms, imports, and exports. The private households, firms, and governments in different regions interact through trade.

In the model, there is a global component consisting of global transportation and banking. The global transportation sector redeems its service with the difference between the free on board (f.o.b.) and cost, insurance, and freight (c.i.f.) values for a particular commodity shipped along a specific route. The global bank allocates the investment good to all firms according to global savings and rate of returns to capital.

The GTAP database version 5 was used with a base year of 1997. The database, which was constructed primarily from regional Input/Output tables and trade and protection datasets, contains 66 regions/countries and 57 sectors or commodity groups. Hertel provided detailed explanations of the GTAP model and database [25].

The extended version of the GTAP model (GTAP-E) was used in this analysis because it incorporates energy substitutions and CO_2 emissions from the combustion of fossil fuels into the standard GTAP model. Inclusion of the

CO_2 emission component in the model enabled us to simulate the impact of CO_2 emission control and taxation by directly altering CO_2 emission levels and imposing CO_2 emission taxes. The impact of CO_2 emission reductions and taxation on the price of a specific type of energy depends on the carbon content of the energy and demand shifts among various energy types. Adding carbon costs based on their carbon contents to the existing prices of various forms of energy may not fully represent their actual market prices after imposing a CO_2 emission tax or reducing CO_2 emissions. This is because controlling CO_2 emissions or imposing a CO_2 emission tax is also likely to cause demand shifts from one type energy to another, in addition to raising energy production costs. Therefore, allowing for energy substitutions would better reflect the reality of energy markets. In addition, international trade in CO_2 emissions is allowed in the model to enhance the economic efficiency of global CO_2 emission control. In other words, a given target of global CO_2 emission reduction will be achieved at a lowest possible cost while the resultant impact on energy prices may be different across regions and countries. The model divides the world economy into eight regions: the United States of America, the European Union (EU), Eastern Europe and the Former Soviet Union, Japan, other Annex 1 countries, net energy exporters, China and India, and the rest of the world (ROW). For each region, there are eight sectors/commodity groups: agriculture and forestry, coal, oil, natural gas, petroleum and coal products, electricity, energy intensive industries, and other industries and services. More detailed descriptions of the GTAP-E model can be found in Burniaux and Truong [27].

Running a CGE model usually involves model calibration using a base year data and projections of changes in endogenous variables against their benchmark levels in the base year after introducing a policy shock. The shock variables used in this analysis were CO_2 emission reductions and taxes. Six CO_2 emission reduction scenarios were simulated, including the emission reduction targets committed by Annex 1 countries under the Kyoto Protocol, and 10%, 20%, 30%, 40%, and 50% reductions in global CO_2 emissions. Under the Kyoto Protocol scenario, CO_2 emissions were assumed to reduce by 8% for the EU, 7% for the US (even though the US government did not ratify it), and 6% for Canada and Japan, respectively. No emission reduction was required for other regions under the Kyoto Protocol. Five emission tax rates were analyzed: US\$25, 50, 75, 100, and 125 per metric ton of CO_2 emitted.

2.2. Comparisons of fossil and biomass energy production

The comparative analysis was based on both feedstock and electricity production. Two types of woody biomass originating from short-rotation hybrid poplar plantations and logging residues were considered. The rotation length and lifetime, the time span from initial establishment (planting) to final harvest, was presumed to be 7 years for poplar. After each rotation, the plantations would be reestablished.

Biomass yield and production costs were derived primarily from the Oak Ridge Energy Crop County Level Database (ORECCL) [28]. The production costs included those of establishment, annual maintenance and management, harvest, and land rent[1]. Both fixed and variable costs were incorporated. Land rent was assumed to be US\$123.50 $ha^{-1} yr^{-1}$, reflecting the national average Conservation Reserve Program (CRP) rent for the land used for energy crop production. Because this study was intended to assess the general competitive status of woody biomass energy, national average production costs and biomass yield were used. To estimate the national average production cost for poplar plantations, we first identified the median production cost in each biomass-producing county listed in the ORECCL database. The mode[2] of the counties' median costs was then determined and used as the national average production cost. The same approach was used to estimate the national average biomass yield, which was 11.21 dry Mg $ha^{-1} yr^{-1}$ (5 dry tons $ac^{-1} yr^{-1}$) for poplar. Two other yield scenarios including 50% and 100% increases from the base yield were also considered for sensitivity analysis. The production costs were adjusted for yield differences based on the statistical relationship between biomass yield and production costs estimated using the ORECCL data. All costs incurred during the rotation period were annualized using a 6.5% real discount rate.

The procurement costs of logging residues from conventional forests were derived mainly from Puttock [16]. An integrated harvesting system was used to harvest both conventional wood products and fuel wood from logging residues. The system involved a feller-buncher/grapple to skid whole trees to a landing, flail processing at the landing, and a tub-grinder for residue comminution. The costs were estimated in two approaches: the joint cost and the marginal cost. In the joint cost approach, the total production costs were distributed between conventional wood products (sawtimber and pulpwood) and fuel wood. On the other hand, in the marginal cost approach only additional costs from the conventional logging operation were counted for biomass (fuel wood) production costs. No stumpage values were allocated to fuel wood in both approaches.

The energy content was assumed to be 19.19 GJ dry^{-1} Mg (16.5 million Btus per dry ton) for the woody biomass. The production costs including delivery costs were calculated based on per unit energy produced, which were then compared to the national average price of delivered coal in the base year and under various CO_2 emission reduction and tax scenarios.

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[1] The ORECCL data did not include land rent.

[2] The mode of the present value of production costs (excluding land rent) discounted at 6.5% over a 7-year rotation for poplar plantations was \$387 ha^{-1} (\$955 ac^{-1}) [28].

Table 1
Costs and performance characteristics of electricity generating systems

Cost and characteristics	Conventional pulverized coal	Integrated coal gasification combined cycle	Biomass gasification combined cycle
Size (MW)	400	428	100
Initial capital costs including contingencies (US\$ kW^{-1})	1119	1338	1725
Variable operation and maintenance (O&M) costs(US\$ MWh^{-1})	3.38	0.80	2.90
Fixed O&M costs (US\$ MW^{-1})	23.41	32.67	44.95
Heat rate (MJ kWh^{-1})	9.90	8.30	9.40

Source: Energy Information Administration [9].

Three electricity generation systems were analyzed: biomass gasification combined cycle, conventional pulverized coal, and integrated coal gasification combined cycle. Cofiring coal with biomass could be another promising alternative for using biomass in electricity generation. However, due to the lack of data, complexity of economic analysis, and potential technical complications such as the deleterious impact of biomass ashes, no cofiring system was considered. The costs and performance characteristics of these systems, adopted from the Energy Information Administration [29], are presented in Table 1. The scale of the biomass electric plant was smaller than that of coal power plants because of the high cost of delivering biomass over a long distance. The biomass gasification combined cycle system was chosen because it represents the most economically and technically promising power generating system for biomass now and in the near future [30]. All three systems were assumed to operate at commercial scales for 20 years. The costs included the initial capital investment and those for operation and maintenance. The fuel cost was determined based on the price of delivered biomass and coal. The delivery cost for woody biomass was estimated at US\$8.27 dry^{-1} Mg (US\$7.5 dry^{-1} ton) with an average transportation distance of 120 km. It was assumed that 6% of the biomass was lost during storage and transport. The national average price of coal received by power plants was derived from the Energy Information Administration [31]. Using these data, the costs per unit of electricity generated from each system were estimated. The electricity production cost of the biomass gasification combined cycle system was then compared with that of the conventional pulverized coal system and the integrated coal gasification combined cycle system. All costs and prices in this analysis were measured using 1997 constant US dollars.

3. Results

3.1. Impact of CO_2 emission reductions and taxes on energy prices

Reductions in global CO_2 emissions would cause the price of coal delivered to power plants to increase progressively as the marginal cost of controlling emissions rises with the amount of emissions reduced. The coal price would change only slightly if current global CO_2 emissions are reduced by less than 10%. For instance, reaching the CO_2 emission targets committed by Annex 1 countries under the Kyoto Protocol would lead to only about an 8% increase in the coal price. However, if global CO_2 emissions are cut by 20% or more, coal prices would significantly increase. For a 50% global CO_2 emission reduction, US coal prices would increase by almost three fold from the 1997 base-year level. Imposing CO_2 emission taxes would cause coal prices to increase proportionally to the tax rate. Coal prices in US markets would go up by some 58% for each US\$25 $Mg^{-1}CO_2$ emission tax imposed (Table 2).

3.1.1. Biomass feedstock production

To assess the economic efficiency of the woody biomass production systems identified earlier, we compared biomass feedstock production costs (annualized costs of delivered biomass) with the price of delivered coal. Instead of comparing the farm gate price of biomass with the wellhead price of coal, we added delivery costs into the analysis for two reasons. First, end users are more interested in delivered prices than farm gate or wellhead prices. Second, delivery costs for woody biomass and coal on a per unit energy basis are considerably different. Therefore, accounting for delivery costs would better reflect their competitiveness status. At a yield of 11.21 dry Mg $ha^{-1} yr^{-1}$, biomass production and transport costs were estimated at about US\$3.01 GJ^{-1} for hybrid poplar plantations. Given the fact that the current price (1995–1999 national average price) of delivered coal is around US\$1.21 GJ^{-1} [27], the biomass production costs have to be reduced by almost 60% in order to compete with coal. Without significant reductions in biomass production costs, yield would have to substantially increase. The yield at which biomass produced from energy plantations would be comparable with coal would be at least 38 dry Mg $ha^{-1} yr^{-1}$ for poplar (Fig. 1).

Imposing a CO_2 emission tax would enhance the competitiveness of woody biomass energy production. At current yield and production costs, hybrid poplar would not be comparable with coal unless CO_2 emissions are taxed at about US\$65 Mg^{-1} CO_2. An increase in biomass yield would improve the cost effectiveness of biomass

Table 2
Percentage changes in the price of delivered coal under different CO_2 emission reduction and tax scenarios

Scenario	Change in coal price (%, base year = 1997)
CO_2 emission reductions	
Kyoto protocol	8.13
10% reduction of global emissions	7.51
20% reduction of global emissions	31.01
30% reduction of global emissions	84.48
40% reduction of global emissions	189.95
50% reduction of global emissions	384.25
CO_2 emission taxes	
US\$25 Mg^{-1} CO_2	58.00
US\$50 Mg^{-1} CO_2	116.01
US\$75 Mg^{-1} CO_2	174.01
US\$100 Mg^{-1} CO_2	232.01
US\$125 Mg^{-1} CO_2	290.01

Notes: Under the Kyoto scenario, a 7% emission reduction in the US was assumed. Under a 10% global aggregate emission reduction, the US would not have to reduce domestic emissions that much because reducing emissions in some other countries would be less costly than in the US, leading to a smaller domestic coal price increase than under the Kyoto scenario.

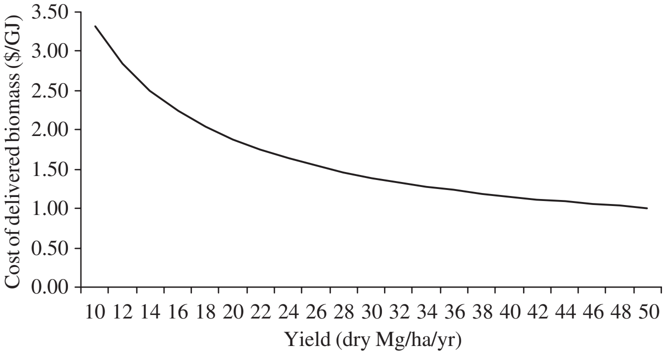

Fig. 1. Biomass production costs at different yields.

energy production. If biomass yield reaches 16.81 dry Mg ha^{-1} yr^{-1} (7.5 dry tons ac^{-1} y^{-1}) and 22.42 dry Mg ha^{-1} yr^{-1} (10 dry tons ac^{-1} yr^{-1}), the required CO_2 emission tax would reduce to US\$44 and US\$33 per metric ton of CO_2, respectively. Alternatively, CO_2 emissions would have to be reduced by 30–40% for poplar plantations to become competitive with coal in terms of feedstock production (Fig. 2).

The production of biomass energy from logging residues using the integrated harvesting system appeared more economical. The estimated marginal cost of procuring fuel wood from logging residues was US\$0.26 GJ^{-1}, and the full cost was about US\$0.54 GJ^{-1}[16]. Adding the delivery cost, the total cost of delivered biomass produced from logging residues reached US\$0.69 GJ^{-1} for the marginal cost method and US\$0.97 GJ^{-1} for the full cost method, respectively (Fig. 2). These costs, as reported by Puttock [16], are considerably lower than those in Europe, but quite comparable with those reported in New Zealand [32].

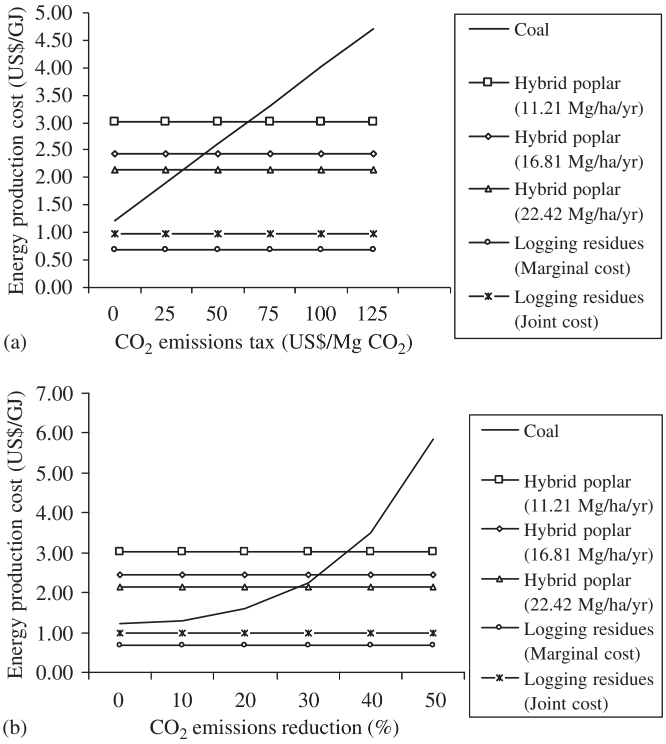

Fig. 2. Production costs of delivered biomass feedstocks and coal under various CO_2 emission taxes and reductions. *Notes*: For logging residues, "marginal cost" indicates that only additional costs from the conventional timber harvest were counted for fuel wood production, and "joint cost" means that total production costs were distributed between conventional wood products and fuel wood. The yield of poplar plantations was measured in dry biomass.

According to the estimated production costs of feedstock, logging residues are already competitive with coal. However, the conversion cost from primary energy (woody biomass) to secondary energy (electricity) was not included here, which will be discussed later in electricity production. In addition, other benefits and costs may also arise from the removal of logging residues. These benefits include, among others, reductions in site preparation and planting costs, and fire and disease risks. On the other hand, potential adverse effects include concern about reductions in soil productivity on sites with low native fertility. Due to data limitations, these benefits and costs were not incorporated in this analysis.

3.2. Electricity generation

Without considering CO_2 emission costs, electricity generation costs using the conventional pulverized coal system and the integrated coal gasification combined cycle system were estimated to be 3.24 and 3.19 cents kWh^{-1}, respectively. The electricity production cost using the biomass gasification combined cycle system fueled by poplar biomass would be almost twice as high as that using the coal conventional or gasification system. Compared to the integrated coal gasification system, the biomass gasification system would cost more in all categories, particularly in initial capital expenditure and fuel. The initial investment on a per unit plant capacity basis for the biomass gasification system would be about 50% higher than that for the coal conventional system (Table 1). The non-fuel cost (capital and maintenance and operation cost) of electricity generation fired by biomass was almost the same as the total electricity production cost using the coal conventional and gasification systems. Therefore, without improvements in biomass electric generation technology and/or inclusion of environmental benefits, it would be impossible for biomass to compete with coal in electricity production. Excluding environmental/social benefits, if the non-fuel cost is reduced by 25%, biomass would be able to compete with coal at a delivered price of US\$15 dry Mg^{-1} or lower. This seems achievable for logging residues if only the marginal costs are counted.

Meanwhile, the fuel cost made up almost half the total electricity cost in the biomass gasification system while it was only about one-third of the total cost in the coal conventional or gasification system. Thus, reducing the fuel cost through increasing the productivity and efficiency of the biomass production and transport systems would also have significant implications for enhancing the competitiveness of electricity generated from biomass. For instance, a US\$10 Mg^{-1} reduction in the price of delivered biomass, the electricity production cost would fall by about 0.5 cent kWh^{-1}.

Biomass procured from logging residues was more cost effective than energy plantations. Imposition of an emission tax at around US\$25 Mg^{-1} CO_2 would enable logging residues to be comparable with coal. Given current average biomass yield (11.21 dry Mg ha^{-1} yr^{-1}) and electricity generation technologies, for poplar plantations to become competitive with coal in electricity production, CO_2 emissions would have to be taxed at US\$100 Mg^{-1} CO_2 or higher. If biomass yield reaches 22.42 dry Mg ha^{-1} yr^{-1}, biomass from poplar plantations would be able to compete with coal at an emission tax of US\$75 Mg^{-1} CO_2 for the coal gasification system and US\$65 $Mg^{-1}CO_2$ for the conventional pulverized coal system.

Similarly, controlling CO_2 emissions would enhance the economic potential of woody biomass for electricity generation. For a 20–30% reduction in global CO_2 emissions, logging residues would be able to compete with coal in electricity production. However, a 40% or higher reduction in global CO_2 emissions would be needed for hybrid poplar plantations to compete with coal in electricity production (Fig. 3).

Biomass would become quite a promising fuel for electricity generation with improved technologies in energy conversion and biomass feedstock production and the inclusion of social/environmental benefits of bioenergy. For instance, if the non-fuel cost in biomass electric production is reduced by 25% and if CO_2 emissions are taxed at US\$25 $Mg^{-1}CO_2$, a biomass price of US\$30 dry Mg^{-1} would make it competitive with coal in electricity production. This price exceeds the estimated full cost of delivered logging residues and is very close to the cost of delivered poplar biomass if a yield of 22.42 dry Mg ha^{-1} yr^{-1} is achieved.

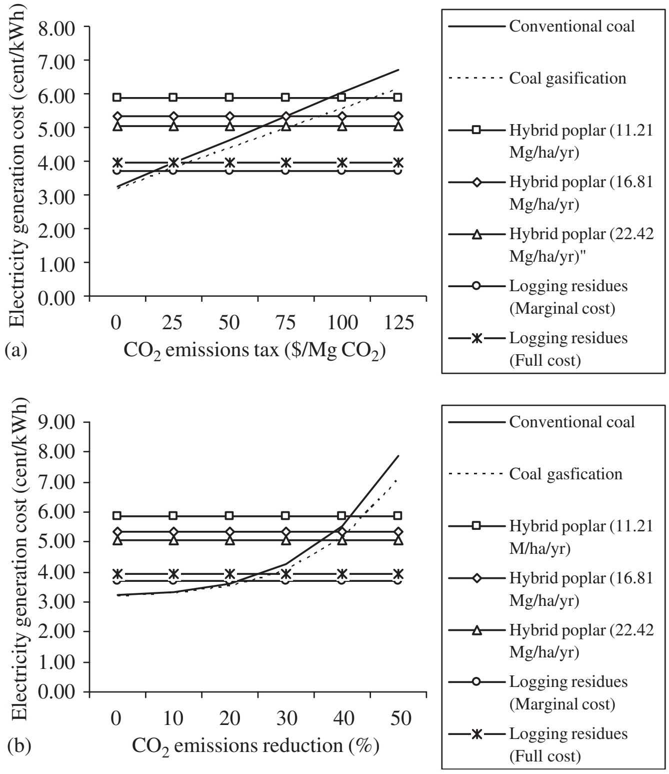

Fig. 3. Electricity production costs by fuel types under different CO_2 emission taxes and reductions. *Notes*: For logging residues, "marginal cost" indicates that only additional costs from the conventional timber harvest were counted for fuel wood production, and "joint cost" means that total production costs were distributed between conventional wood products and fuel wood. The yield of poplar plantations was measured in dry biomass.

4. Conclusions

Increasing concerns about atmospheric CO_2 concentration have further aroused our interest in biomass energy. Woody biomass energy is thought to be nearly CO_2 neutral and is likely to emerge as a means to offset CO_2 emissions from the combustion of fossil fuels. This study examined the cost competitiveness of woody biomass relative to coal in feedstock and electricity production in the US under several CO_2 emission reduction and taxation scenarios. Woody biomass produced from poplar plantations and logging residues were analyzed. As demonstrated previously in case studies [33,34], without counting environmental benefits woody biomass from energy plantations has no cost advantage over coal in electricity or even biomass feedstock production. However, imposing a CO_2 emission tax or reducing global CO_2 emissions would considerably increase coal prices in the US, enhancing the economic potential of woody biomass. In terms of biomass feedstock production costs, logging residues are already comparable with coal. Biomass from poplar plantations at a yield of 11.21 dry Mg $\text{ha}^{-1}\,\text{yr}^{-1}$ would become competitive with coal if CO_2 emissions are taxed at a rate of about US\$65 Mg^{-1} CO_2. For a 50% increase in yield (16.81 dry Mg $\text{ha}^{-1}\,\text{yr}^{-1}$), the CO_2 emission tax at which biomass could compete with coal would reduce by about US\$20 Mg^{-1} CO_2. A global CO_2 emission reduction between 30% and 40% would be needed for hybrid poplar to become as cost effective as coal.

Similarly, coal has cost advantages over biomass in electricity generation under current technologies and market conditions. For a CO_2 emission tax between US\$75 Mg^{-1} and US\$125 Mg^{-1}, biomass from poplar plantations would be able to compete with coal in electricity production. Compared to energy plantations, biomass recovered from logging residues using integrated harvesting systems showed higher economic potential for electricity production. The electricity generation costs using coal and logging residues would be comparable at an emission tax of US\$25 Mg^{-1} CO_2. Reaching the CO_2 emission targets set up under the Kyoto Protocol would have little impact on improving the cost competitiveness of woody biomass energy. However, logging residues would be as cost effective as coal when global CO_2 emissions are curtailed by 20–30%, whereas global CO_2 emissions would have to be reduced by at least 40% for poplar plantations to compete with coal in electricity production.

Though CO_2 emission taxes or reductions would strengthen the competitiveness of woody biomass energy, costs remain the major impediment for woody biomass energy to compete with fossil fuels. Advances in biomass electric generation technologies and improvements in the productivity of biomass production, harvesting, and transport systems are clearly the key to enhancing the bioenergy share in US energy markets. According to Graham et al. [33], by 2020 about 300 million Mg of woody biomass can be produced annually from energy plantations in the US at a delivered price of US\$2.15 GJ^{-1} or lower. With improved power generation technologies and inclusion of more social and environmental benefits and costs in energy production and consumption decision-making, woody biomass energy could be an alternative, cost-effective energy source. In addition to carbon benefits, woody biomass energy possesses other environmental and social benefits such as reductions in SO_2 and NO_x emissions, revitalization of rural economies, and enhancement of energy security. There is a significant amount of idle and marginal agricultural land suitable for biomass production in the US besides environmental benefits, using these lands for biomass energy production would benefit rural communities by creating jobs and income and diversifying local economies. Substitutions of biomass energy for fossil fuels may also help reduce oil imports and ultimately the nation's economic and energy vulnerability caused by heavy dependence on foreign oil.

This analysis drew on existing findings on the economics of biomass energy production in the US. Our data represent national average biomass yields, biomass and electricity production costs, and energy prices. As a result, our results reflect only the national average or general competitive status of woody biomass energy relative to coal in terms of feedstock and electricity production. These results would have important implications for the economic potential of large-scale production of woody biomass energy, but might not reflect regional variations or special cases. Local, niche markets may be sufficiently different. Indeed, electricity production fueled by biomass alone or through cofiring biomass with coal is already competitive in some local markets or under certain circumstances [17,35]. Furthermore, many factors influence energy prices. Energy prices do fluctuate from time to time due to economic and non-economic reasons. In fact, energy prices have climbed significantly in recent years. If this trend continues, the cost competitiveness of woody biomass could be further improved. Hopefully, this study has provided a general picture about the competitive status of woody biomass energy in the US under the consideration of potential CO_2 emission taxes and reductions. Our analysis can be expanded by adding and comparing more energy and biomass production scenarios such as cofiring, ethanol production, and utilization of small diameter trees thinned/harvested from fire/fuel management or conventional forest management as adequate data become available. Further studies are also suggested to incorporate other relevant economic, institutional, and technical factors into the analysis and to periodically update the economic evaluation as technologies for biomass production and energy conversion advance.

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