Climate Change Mitigation Potential in Agricultural and Forestry Sector: The Impact of Expanded Woody Biomass Co-firing on Global Climate Stabilization

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Abstract. The impact of expanded woody biomass co-firing in electric power production on global climate stabilization is studied using the Global Biosphere Model (GLOBIOM) and the World Induced Technical Change Hybrid (WITCH) model. The study finds that, even with a ratio of biomass to total feedstock less or equal to 10%, biomass co-firing can help achieve the climate policy goal of 2 °C temperature increase above the pre-industrial level by the end of the century at a lower cost. The policy cost can be further reduced if the ratio of biomass to total feedstock increases via technical progress or biomass supply increases. The study also shows that there is enough biomass potential from agriculture and forestry to progressively replace current nuclear energy supply with bioenergy from co-fired plants. However, replacing current nuclear energy supply with bioenergy produced from co-firing in order to deal with nuclear energy production safety concerns will lead to a high policy cost in terms of total GDP loss. The study finally reveals that future biomass trade from sub-Saharan Africa & Latin America to Europe, North America, and China may be needed for climate policy goals to be reached via biomass co-firing.

Keywords: Global woody biomass supply · Global food price
Nuclear energy phase out

1 Introduction

It is well acknowledged in the literature [1] that mitigation in agricultural and forestry (AF) sector can occur through changes in crop management practices, improvement in livestock management, alteration of crop mix, promotion of good forest management practices, and expansion of bioenergy production as substitutes to traditional fossil energy sources for transportation (via liquid biofuels) & electric power production (via biomass co-firing with coal). While it is desirable that all the above AF mitigation options be deployed to increase mitigation potential, co-firing woody biomass (from short rotation tree plantations and industrial forest logging residues) with coal appears to be an obvious option for short and medium run mitigation for technological and environmental reasons. Technologically, biomass co-firing requires only modest

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incremental investment to retrofit existing coal-fired plants or building new biomass co-firing plants [2, 3]. Environmentally, supply of perennial short rotation trees for woody biomass (e.g. Poplar and Eucalyptus) requires little or no tillage before planting and may require scant fertilizer usage to reach maturity [4]. Hence, landscape level environmental impacts such as soil erosion and nutrients loss into surface and groundwater are minimized with woody biomass feedstock production as compared to biomass feedstock production from annual crop residues [4–6].

Alternative uses of woody biomass for energy production which includes converting woody biomass feedstock into second generation liquid biofuels has been a disappointment [7]. Furthermore, woody biomass co-firing is recognized to have high greenhouse gas (GHG) mitigation potential. In fact, Life-cycle analysis (LCA) studies demonstrate that when the quantity of fossil fuels displaced is accounted for, the mitigation potential from woody biomass co-firing could reach up to a carbon sink rate of 400 g CO_2e-C.m^{-2} [8, 9]. Climate change mitigation through agricultural and forestry (AF) sector, particularly through biomass co-firing with coal, could be a bridge to the future for short and medium run GHG emissions reduction [10]. For significant but not immediately available investments in low carbon technologies (e.g. wind and solar) are needed to stabilize the global climate by the end of the century. These investments are expensive and may occur late in the century because of the slow capital turnover in the energy sector and the cost ineffectiveness of the current low carbon technologies. Given the current and the future potential threats of climate change [11], there is urgency for short and medium run mitigation actions to reduce GHG emissions.

The objective of this paper is to evaluate the impact of biomass co-firing on global climate stabilization at the CO_2 concentration level of 450 parts per million (ppm) by the end of the century. Specifically, the study does the following: (a) estimate the world economic potential for forest residues production from industrial forest logging and short rotation tree plantations for biomass, (b) evaluate the implications of woody biomass production on land use change, food price increase, and land use CO_2 emissions, (c) measure the impact of the woody biomass co-firing on global CO_2 emissions and GHG abatement. To reach these objectives, three fundamental research questions are to be addressed: (i) what are the drivers of woody biomass production from short rotation tree plantations and forest logging residues?, (ii) what are the implications of such biomass production activities on land use change, food prices and land use CO_2 emissions?, (iii) what is the contribution of such biomass utilization to the climate stabilization goals?

To address these fundamental research questions, this paper proceeds by linking two global models. The Global Biosphere Management Model (GLOBIOM), an agricultural and forestry sector optimization model that includes global crops, livestock and biomass production activities is used to estimate the global potential woody biomass production. The impact of the woody biomass co-firing on emissions reduction and the global climate stabilization is analyzed using the World Induced Technological Change Hybrid (WITCH), an integrated assessment model. This study departs from the previous literature (e.g. [12]) in that: (a) land use has been implicitly modeled to minimize competition between woody biomass production and food production by including forest logging residues in the stock of biomass feedstock, (b) Cellulosic grasses such Switchgrass and Miscanthus are not included in the feedstock potential to consider only hard wood with high energy content for coal-fired power plants system.

2 Materials and Methods

2.1 Description of GLOBIOM

The Global Biosphere Management Model (GLOBIOM) is a global agricultural and forestry sector optimization model built to tackle several global policy challenges related to bioenergy, food security and environmental management [13]. The structure of the model is similar to the U.S agricultural and forestry sector optimization model [14] and it maximizes the total welfare from agricultural and forestry sector under several resource constraints. Crop yields are simulated from the Environmental Policy Integrated Climate (EPIC), a biophysical crop growth model [15]. The model has a total of 17 crops modeled through EPIC based on fertilization level and irrigation. Other crops not simulated by EPIC are in number of 17 as well. These latter crops are modeled according to two management systems (irrigated or rain fed). In addition, two types of woody biomass sources including short rotation trees and residues from industrial forest logging are simulated.

The structure of land management allows short rotation trees to be grown on land that are marginal to crop production and therefore minimizing direct competition between cropland and short rotation tree plantations. However, minimal land competition may occur when areas cleared through deforestation are reconverted into short rotation tree plantation instead of food crops. This land competition occurs only if the marginal value of biomass production is superior to the marginal value of crop production. To further make sure that land competitions between food crops and biomass crops is minimized, the model requires that food be produced to dynamically satisfy minimum predetermined food calorie demand constraints up until the last simulation year (2100). The model is calibrated so as to replicate the base year (2000) data as reported by the Food and Agriculture Organization (FAO). GLOBIOM is a recursive model which runs up to 2100-time horizon with 10 years' time steps. The model is flexible for outputs to be aggregated into sub-regional dataset of interests to be passed on to energy models such as WITCH.

2.2 Description of WITCH Model

The World Induced Technical Change Hybrid (WITCH) model is an integrated assessment model (IAM) built on the optimal growth modeling framework. Consumption is assumed to be maximized under the constraint that it must equal production net of investments [16]. Production and investment functions are defined to represent a medium complexity energy sector. A build-in climate module allows accounting for GHG emissions throughout the whole economy. Emission caps are defined for various climate stabilization policy targets. One feature that distinguishes WITCH from other IAM is the game theoretical framework that is utilized to find the equilibrium for the 13 regions of the model. The 13 regional aggregations are CAJAZ

(Canada, Japan and New Zealand), CHINA (including Taiwan), EASIA (East Asia including Indonesia), INDIA, KOSAU (South Korea, South Africa, and Australia), LACA (Latin America, Mexico and Caribbean), MENA (Middle East and North Africa), WEST EUROPE (Old EU countries), EAST EUROPE (new EU countries), SASIA (South Asia), SSA (Sub-Saharan Africa), TE (Transition Economies which includes non-EU Eastern European countries and Russia), and the USA.

In WITCH, energy is an input to good and services production and comes as non-electric (NEL) and electric (EL) energy. Non-electric energy is from oil, gas and first generation liquid biofuels as well as traditional biomass. Electric energy comes from hydroelectric, nuclear, wind, solar, and fossil fuels nest (coal, oil, and gas). Woody biomass and coal are modeled as one electric energy nest with infinite elasticity of substitution. Each can operate under two technologies that differ by costs. Coal/biomass can be pulverized (ELP) or gasified through integrated gasification combined cycle (IGCC) with carbon capture and storage (CCS) to produce electricity. The original WITCH model functions with separate combustion of coal and biomass feedstocks. Co-firing coal with biomass can improve the efficiency of the mix (40%–50%). The original WITCH model is then modified to simulate two biomass co-firing technologies [2]. The first consists of directly co-firing coal with woody biomass in a single boiler. As a result, a mixture above 10% of biomass would reduce the efficiency [17]. The second consists of indirectly co-firing biomass by first converting it into a gaseous fuel before burning it with coal. In this case, there is no physical limit to the percentage of biomass in the mixture. Any excess of biomass not co-fired in the model is used in a stand-alone biomass plants even though the efficiency is reduced. A brief description of biomass and coal nest for electric power production in WITCH with the newly added co-firing technologies (in dash) is given in Fig. 1.

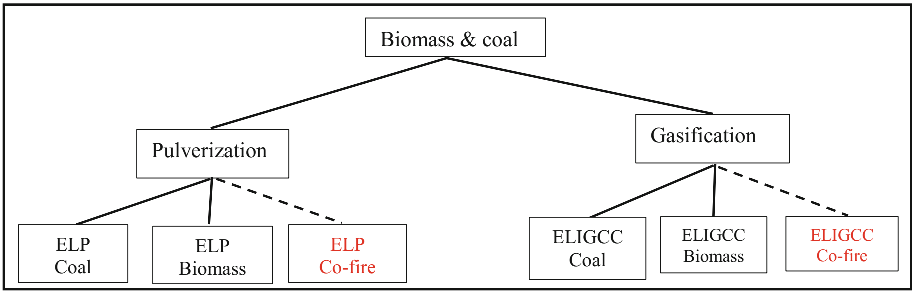

Fig. 1. Coal and biomass electric power production technology (all technologies function with carbon storage and capture technology).

3 Data and GLOBIOM Simulation Results

3.1 Industrial Forest Logging Residues Biomass

Biomass from forest logging residues originates from managed forests around the globe. In GLOBIOM, forest is managed for saw logs, pulp logs, other industrial logs, traditional fuel woods and biomass for bioenergy. Biomass price is simulated from $7 US/GJ to $40 US/GJ. The world potential biomass supply from forest logging residues varies from 0 EJ in 2000 to about 146 EJ by 2100. While this supply function is less sensitive to time trend (because of the fixed managed forest areas) it is sensitive to prices. The highest potentials could be reached when price incentives are at their highest levels. Policies that encourage utilization of biomass feedstock in co-firing (e.g. the renewable fuel standard (RFS) policies in several states in the U.S. and in Europe) could increase market incentives for woody biomass production and trade. The group of regions including LACA, SSA and EASIA are the big producers and regions such as CHINA, USA, INDIA and WESTERN EUROPE may be potential future importers because of their high dependence on coal for electric power supply. This may open future biomass trade businesses across continents for low carbon electric power production.

3.2 Short Rotation Trees Biomass Production, Land Use and World Food Prices

Biomass from short rotation trees is obtained through plantation of poplar trees on land areas previously covered by natural vegetation, grassland and unmanaged forests. Natural vegetation land cover and grassland are marginal to agriculture crop production. However, since biomass from short rotation trees is grown on land areas previously covered by other existing vegetation and grasses, indirect land use emissions may occur from such biomass production activities. Biomass supply potential from short rotation tree plantations varies from 1.2 EJ in 2000 to about 158 EJ in 2100. In contrast with the supply schedule of biomass from forest logging residues, biomass from short rotation trees is less sensitive to price but more sensitive to time. This means that the full potential could not be reached based on price incentives alone. More time is needed for full conversion of available land areas into short rotation tree plantations. Of course, the potential estimated for short rotation trees biomass is linked to yield assumptions. Gradual increases in yield over the simulation period due to technical change could increase the supply potential.

To reach the economic potential of short rotation tree plantations, the land area needed will vary from 0 ha in 2000 to 5.6 billion ha in 2100. This land area is more than three times the current global crop land areas. Therefore, significant dedicated land areas will be required to reach high biomass supply potential from short rotation tree plantations unless yields improve significantly. Given the weak substitutability between land use from crops and short rotation trees in GLOBIOM, the potential impact of biomass production on food price is reduced. It is important to notice that the group of regions such as LACA and SSA which are not big coal users are endowed with more land areas for biomass production than other regions in the model. Therefore, other may need to import biomass processed into chips from LACA and SSA to implement significant co-firing policy. These land use changes have no significant effects on food prices. The world food prices index increases to reach 1.2 in 2020 due significantly to first generation biofuel mandates in various parts of the world including the U.S and Europe. The model assumes that first generation biofuel mandates are not continued after 2020. Prices decrease slowly to reach their pre-mandate levels by the end of the century.

3.3 Land Use CO_2 Emissions and Co-firing Technical Data

WITCH does not have endogenously estimated values of land use CO_2 emissions. They are computed in GLOBIOM based on emissions from deforestation, afforestation and indirect land use change emissions. To capture the relationship between land use CO_2 emissions, carbon price, and woody biomass production; higher order polynomial functions with interactive terms and time trend have been econometrically estimated to predict the level of land use CO_2. This allows land use CO_2 levels to be endogenous in WITCH and reflected in climate change policy scenarios. To implement the co-firing experiments in the WITCH model, several parameters related to the investments in retrofitting existing coal plants as well as the operating and maintenance costs are drawn from the literature [2, 18].

4 WITCH Model Simulation Results

The paper conducts four policy experiments all based on the climate policy target of 2 °C above the pre-industrial level by 2100. In the first policy experiment, coal-fired plants producing electricity using pulverization and gasification technologies are set to progressively phase out by constraining investments in these technologies to zero starting from 2020 with 10% biomass in the feedstock mix (Experiment 1). In the second experiment, the ratio of biomass to total feedstock is progressively increased up to 30% for pulverized plants and up to 100% for gasified plants (Experiment 2). In the third experiment, the supply of woody biomass is allowed to increase by doubling land areas dedicated to short rotation trees (Experiment 3). In the fourth policy experiment, nuclear energy is allowed to progressively phase out by setting investments in that technology to zero starting from 2050 (Experiment 4). Simultaneously with this last experiment, the supply of woody biomass for co-firing is increased by setting land use for all years at the predicted 2050 level (an average of 3.8 billion ha). This fourth policy experiment is justified by safety concerns of nuclear energy production due to past nuclear accidents (Chernobyl in 1986, Fukushima in 2011, etc…). Also, in the last three experiments, progressive pure coal fired plants phase out by 2020 is maintained. The obtained results in the four policy experiments are presented in terms of changes in CO_2 emissions in electric sector, total GHG abatement, and policy costs measured as the total world GDP loss relative to the situation without the co-firing policy in place. Note that the base scenario functions via a cap-and-trade to meet climate policy targets without biomass co-firing.

4.1 Changes in CO_2 Emissions from the Electric Sector

The progressive replacement of pure coal plants by biomass co-firing plants is expected to lower in average CO_2 emissions in the electric power production sector. However, progressive replacement of nuclear energy production plants by biomass co-firing plants is expected to increase on average the total CO_2 emissions from the electric sector. The results are presented in Fig. 2. The graphs in Fig. 2 show that the policy experiment 3 in which biomass feedstock supply is increased via doubling of land use dedicated to short rotation trees has produced on average the lowest CO_2 emissions from the electric power production sector. The reason behind this result is that many countries in Europe, North America and Asia who rely on pure coal plants for electric power production do not have enough woody biomass feedstock to implement the policy. Therefore, an increase of biomass supply is necessary to reach the objectives of the co-firing policy. Hence, the main limitation of the first two policy experiments is the unbalance between the supply and the demand of biomass in many regions. As a consequence, the trade of biomass between regions can solve the biomass supply-demand unbalances.

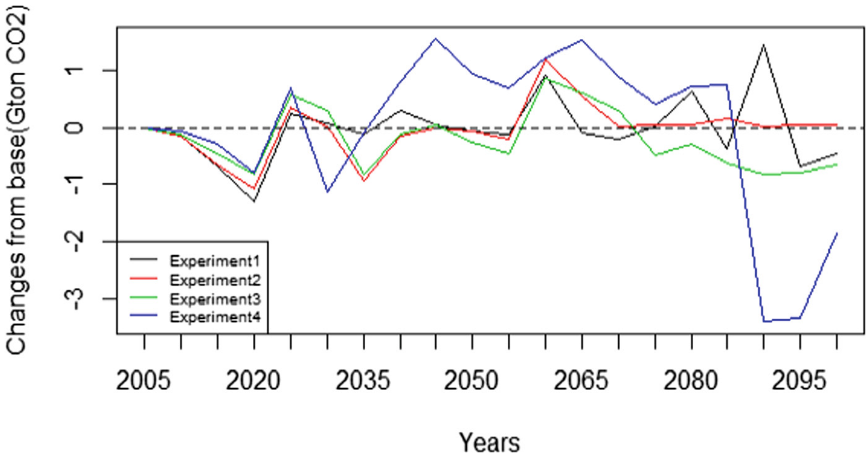

Fig. 2. CO_2 emissions from the electric power production sector measured as the difference of co-firing policy experiments relative to the base emissions with pure coal plants

4.2 GHG Abatement

The total GHG abated is expected to increase as CO_2 and other GHG (e.g. SO_2) emissions drop in average with co-firing policies in place. The GHG abatement trajectories are given in Fig. 3. Significant GHG abatement will only occur starting from 2045 for both the policy experiment 3 where biomass supply is increased through land use and the policy experiment 4. However, the abatement occurring under the policy experiment 4 related to the phase out of the nuclear energy is due to the use of CCS in the last years of the century making the abatement more costly. The first two experiments cause less significant abatement of GHG relatively to the base with pure coal plants.

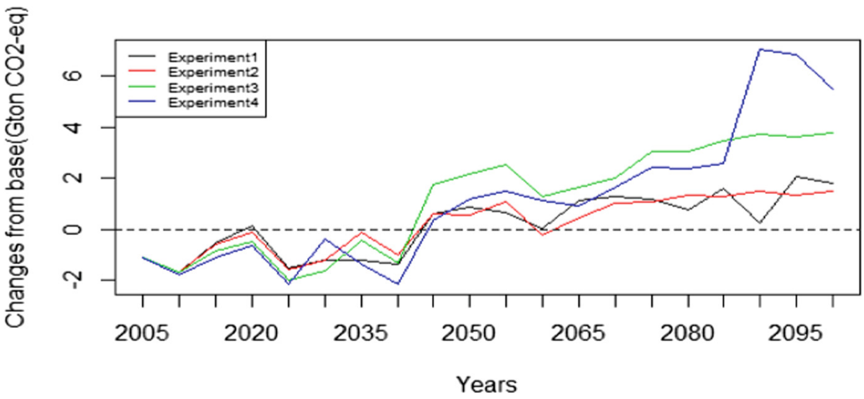

Fig. 3. GHG abatement measured as the difference of each co-firing policy experiment relative to the base emissions with pure coal plants

4.3 Policy Costs

The estimated discounted costs of the four co-firing policy experiments show that progressively phasing out pure coal plants starting from 2020 and replacing them by biomass co-firing (experiment 1) will cost 5.39% of the world GDP versus 5.43% when the co-firing technology is not in place. Increasing biomass to coal ratio up to 30% for pulverized plants and up to 100% for gasified plants (experiment 2) will cost 5.38% of the world GDP or 0.01% less than in the first experiment. Not surprisingly, the policy cost under policy experiment 3 (where biomass supply is increased) is 5.31% of the world GDP which is the lowest of all the experiments. The policy cost is high in the policy experiment 4. In fact, phasing out nuclear energy will increase the policy cost to 6.09% of world GDP given that nuclear energy production is a low carbon technology relatively to any co-firing technology.

5 Conclusion and Discussion

This paper studies the impact of biomass co-firing on global climate stabilization at 2 °C temperature increase above the pre-industrial level by the end of the century. To do this, the global woody biomass supply potential is estimated using the Global Biosphere Management Model (GLOBIOM). The estimated supply of woody biomass is then passed on to the World Induced Technical Change Hybrid (WITCH) model to measure the impact of woody biomass co-firing on CO_2 emissions and GHG abatement. Four policy experiments are conducted under various biomass co-firing settings. In the first policy experiment, coal plants are set to progressively phase out by 2020 in replacement with biomass co-firing plants. The biomass to total feedstock ratio is assumed to increase due to technical progress in the second policy experiment. In the third policy experiment, biomass supply quantity is increased by raising land resources dedicated to woody biomass production. Nuclear energy production is allowed to progressively phase out in replacement with biomass co-firing plants in the fourth policy experiment.

The results suggest that biomass co-firing can help achieve climate stabilization at 2 °C temperature increase above the pre-industrial level by 2100 with lower policy costs. Under the first policy experiment of woody biomass co-firing (with a maximum of 10% biomass constraint) the policy cost is estimated at 5.39% of the world GDP against 5.43% of the world GDP if the co-firing policy is not in place. An increase in woody biomass co-firing ratio (with more than 10% biomass in the mix) will slightly improve the policy cost to 5.38% of the world GDP. The reduction in policy cost relative to the base is higher when supply of woody biomass is allowed to increase through raising land resources dedicated to woody biomass production. In fact, when woody biomass land use is increased from 1 to 2 billion hectares throughout to the end of the century, the policy cost dropped to 5.31% of the world GDP. However, phasing out nuclear energy production system in replacement with biomass co-firing plants will cost 6.09% of the world GDP due to the replacement of a low carbon technology by a more carbon intensive technology though partially renewable energy production sources. The study also shows that the implementation of biomass co-firing technology will require the participation of all the world regions into a global biomass trade. Land abundant regions such as sub-Saharan Africa (SSA) and Latin America have comparative advantages in the production of woody biomass from short rotation trees. Yet these two regions use less coal in the production of energy. Therefore, production and pre-processing of biomass may occur in these regions and ship to others regions that are more dependent on coal in energy production.

Future research that considers more use of woody biomass not only in electric power production but also in transportation fuels production is warranted. These future studies will help find better ways to use agricultural and forestry resources to find solutions to energy and climate change problems in the short and medium terms.

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