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The feasibility, costs, and environmental implications of large-scale biomass energy

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ABSTRACT

What are the feasibility, costs, and environmental implications of large-scale bioenegry? We investigate this question by developing a detailed representation of bioenergy in a global economy-wide model. We develop a scenario with a global carbon dioxide price, applied to all anthropogenic emissions except those from land use change, that rises from $25 per metric ton in 2015 to $99 in 2050. This creates market conditions favorable to biomass energy, resulting in global non-traditional bioenergy production of ~150 exajoules (EJ) in 2050. By comparison, in 2010, global energy production was primarily from coal (138 EJ), oil (171 EJ), and gas (106 EJ). With this policy, 2050 emissions are 42% less in our *Base Policy* case than our *Reference* case, although extending the scope of the carbon price to include emissions from land use change would reduce 2050 emissions by 52% relative to the same baseline. Our results from various policy scenarios show that lignocellulosic (LC) ethanol may become the major form of bioenergy, if its production costs fall by amounts predicted in a recent survey and ethanol blending constraints disappear by 2030; however, if its costs remain higher than expected or the ethanol blend wall continues to bind, bioelectricity and bioheat may prevail. Higher LC ethanol costs may also result in the expanded production of first-generation biofuels (ethanol from sugarcane and corn) so that they remain in the fuel mix through 2050. Deforestation occurs if emissions from land use change are not priced, although the availability of biomass residues and improvements in crop yields and conversion efficiencies mitigate pressure on land markets. As regions are linked via international agricultural markets, irrespective of the location of bioenergy production, natural forest decreases are largest in regions with the lowest barriers to deforestation. In 2050, the combination of carbon price and bioenergy production increases food prices by 3.2%–5.2%, with bioenergy accounting for 1.3%–3.5%.

1. Introduction

There has been strong interest in bioenergy for several decades. A substantial industry of sugar ethanol was developed in Brazil dating to the 1970s in an effort to limit the impact of high crude oil prices on the economy (Tyner, 2008). The U.S. ethanol industry, now the largest in the world with Brazil a fading second (RFA, 2014), has had various motivations (Gardner and Tyner, 2007). Originally, corn ethanol was supported by agriculture because it supported farm incomes (while producing renewable energy and limiting dependence on imported petroleum) (Kane and Reilly, 1989). Its value as a supply of renewable energy has long been questioned by analysis suggesting the net energy of ethanol production could be negative, using as much fossil energy to produce it as the energy content of the fuel itself (Farrell et al., 2006). With significant increase in ethanol use in the early 2000s as an oxygenate in gasoline, replacing methyl tertiary butyl ether, its value had little to do with the energy it used or created. Then, with the renewable fuel standard (RFS2) in the United States and renewable mandates in Europe, the focus on ethanol, and bioenergy more generally, became explicitly a question of its effects on greenhouse gas emissions. Both the U.S. Environmental Protection Agency (EPA) and the European Commission created rules to favor fuels and fuel pathways that had lower greenhouse gas (GHG) emissions (EC, 2015; USEPA, 2015). While ethanol and biofuels have generally received the most attention and have grown in use rapidly over the last decade, even in the United States, most biomass is used for in heat and power, largely in the pulp and paper industry (USEIA, 2014).

While the several decades of interest in bioenergy and rapid expansion of biofuels in the United States and Europe over the past decade have been the source of much analysis, modern commercial biomass energy remains a small source of energy. Biomass energy is estimated to contribute 10% of global energy use but two-thirds of that is in residential use mainly in developing countries. The 18 EJ of industrial biomass energy, including that used to produce biofuels in 2009 compares with 106 EJ of natural gas, 138 EJ of coal, and 171 EJ of oil

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Table 1
Aggregation in the EPPA model extended to represent bioenergy in detail.

Regions and factors	Sectors
Regions	*Energy sectors*
United States (USA)	Coal
Canada (CAN)	Crude oil
Mexico (MEX)	*Conventional crude oil; oil from shale, sand*
Japan (JPN)	Refined oil
Australia-New Zealand (ANZ)	*From crude oil, first- and second-generation biofuels*
European Union (EUR)	Natural gas
Rest of Europe and Central Asia (ROE)	*Conventional gas; gas from shale, sandstone, coal*
Russia (RUS)	Electricity
China (CHN)	*Coal, gas, refined oil, hydro, nuclear, wind, solar, biomass with and without CCS, natural gas combined cycle,*
India (IND)	*integrated gasification combined cycle, advanced coal, and gas with and without CCS*
Dynamic Asia (ASI)	*Agriculture*
Rest of East Asia (REA)	Crops
Brazil (BRA)	*Food crops; biofuel crops (corn, wheat, energy beet, soybean, rapeseed, sugarcane, oil palms, represent. energy*
Other Latin America (LAM)	*grass, represent. woody crop)*
Africa (AFR)	Livestock
Middle East (MES)	Forestry
Factors	*Non-energy sectors*
Capital	Crops
Labor	Livestock
Land	Forestry
Crop land, managed forest land, natural forest land, managed	Energy-intensive industry
grassland, natural grassland, other land	Other industry
Resources	Services
For coal; crude oil; gas; shale oil; shale gas; hydro, nuclear,	Commercial transportation
wind, and solar electricity	Household transport
	Conventional, hybrid, and plug-in electric vehicles

(Vakkilainen et al., 2013). Much of the analysis related to current polices has represented in detail existing technologies and the impact of relatively small changes in production (e.g., Kane and Reilly, 1989; Taheripour and Tyner, 2014). Another thread of research has looked at the large-scale potential of biomass as a major alternative to fossil fuels. These studies indicate an estimated technical potential for bioenergy of 300 and 500 EJ year in 2020 and 2050, respectively, and deployment of 100 to 300 EJ (Berndes et al., 2003; Chum et al., 2011). For example, Rahdar et al. (2014) examined competition for biomass between bioelectricity and biofuels in the United States under a renewable electricity standard and renewable fuel mandates. Wise et al. (2014) evaluated the impact of existing moderate and high (up to 25% of transportation fuel) global biofuel mandates using the Global Change Assessment Model. Melillo et al. (2009) and Reilly et al. (2012) considered large-scale biofuel development with a simplified second-generation biofuel production technology; however, this provided no insight into the potential competition among first- and second-generation biofuel pathways or uses of biomass for fuels, power generation, and industrial heat. Calvin et al. (2014) examine the role of bioenergy under a carbon price but do not fully integrate land, energy, and agricultural markets.[1]

In this paper, we investigate the following: (1) Given the multiple pathways with which biomass can be used to produce energy, how will pathways change over time and across regions, and would certain pathways ultimately prevail? (2) What are the GHG implications of expanding bioenergy when accounting for the potential need to expand cropland or apply nitrogen fertilizer? (3) Where will bioenergy feedstocks be grown? (4) How will large-scale bioenergy production affect food prices? (5) Will land use limitation policy, intended to protect forested land with large carbon stocks, also limit bioenergy expansion by increasing land prices?

We contribute to the existing literature by evaluating the role of bioenergy under a combination of current and additional policy incentives that would scale up the industry to about 150 EJ, the same order as existing oil, gas, and coal energy use. Our analysis employs a global model of economic activity, including, energy, agriculture, and land markets that is augmented to represent bioenergy in detail. We are thus able to illustrate competition among (1) seven first-generation biofuel crops and conversion technologies; (2) an energy grass and a woody crop; (3) agricultural and forestry residues; (4) two lignocellulosic (LC) biofuel conversion technologies, which can operate with and without carbon capture and storage (CCS); (5) an ethanol-to-diesel upgrading process; (6) electricity from biomass, with and without CCS; and (7) heat from biomass for use in industrial sectors. We explicitly represent bioenergy co-products (e.g., distillers' dry grains and surplus electricity), international trade in biofuels, land use change with explicit representation of conversion costs, limits on the blending of ethanol with gasoline, endogenous changes in land and other production costs, and price-induced changes in energy efficiency and alternative vehicle technologies. Hence, compared with previous investigations, we are able to simulate a transition from current use of first-generation biofuels stimulated by a mix of policies in the United States, Europe, and Brazil to a 150 EJ (primary energy) industry in 2015, with a specific transition path.

This paper has five further sections. Section 2 outlines the core economy-wide model used for our analysis. Section 3 sets out the representation of bioenergy in the model. The scenarios implemented are outlined in Section 4. Section 5 presents and discusses results. Section 6 concludes.

2. A global model of the economy, energy, agriculture, and land

Our analysis builds on version 5 of the Economic Projection and Policy Analysis (EPPA) model, a recursive-dynamic, multi-region computable general equilibrium global model of economic activity,

[1] Several partial equilibrium studies are also relevant to our analysis. Using a mathematical programming model of the agricultural and forest sectors in the US, McCarl et al. (2000) examine the competitiveness of biomass-based electricity generation. The authors find that, under existing policies, improved production methods for short-rotation woody crops are needed for biomass to be competitive with coal. McCarl and Schneider (2001) assess the economic and technical potential for agricultural and forestry emissions mitigation in the U.S. under various carbon prices. They find that the optimal responses vary regionally and include soil-based strategies, biofuels, and afforestation. Using a global agricultural model to estimate emissions from land-use change, Searchinger et al. (2008) conclude that U.S. biofuel production increases GHG emissions. Lauri et al. (2014) employ a global partial equilibrium model of the forestry and agricultural sectors estimate woody biomass feedstock supply curves.