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Biomass Energy and Competition for Land

John Reilly and Sergey Paltsev

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Abstract

We describe an approach for incorporating biomass energy production and competition for land into the MIT Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium model of the world economy, that has been widely used to study climate change policy. We examine multiple scenarios where greenhouse gas emissions are abated or not. The global increase in biomass energy use in a reference scenario (without climate change policy) is about 30 EJ/year by 2050 and about 180 EJ/year by 2100. This deployment is driven primarily by a world oil price that in the year 2100 is over 4.5 times the price in the year 2000. In the scenarios of stabilization of greenhouse gas concentrations, the global biomass energy production increases to 50-150 EJ/year by 2050 and 220-250 EJ/year by 2100. The estimated area of land required to produce 180-250 EJ/year is about 2Gha, which is an equivalent of the current global crop area. In the USA we find that under a stringent climate policy biofuels could supply about 55% of USA liquid fuel demand, but if the biofuels were produced domestically the USA would turn from a substantial net exporter of agricultural goods ($20 billion) to a large net importer ($80 billion). The general conclusion is that the scale of energy use in the USA and the world relative to biomass potential is so large that a biofuel industry that was supplying a substantial share of liquid fuel demand would have very significant effects on land use and conventional agricultural markets.

Contents

1. INTRODUCTION

Biomass energy can be used to avoid greenhouse gas emissions from fossil fuels by providing equivalent energy services: electricity, transportation fuels and heat (IPCC, 2000). In 2001, global biomass energy use for cooking and heating was 39 EJ, or 9.3% of the global primary energy use, and biomass energy use for electricity and fuel generation was 6 EJ, or 1.4% of global primary energy use (IEA, 2001; Smeets and Faaij, 2007). The estimates of the global bioenergy production potential vary substantially from a low estimate of 350 EJ/year (Fisher and Schrattenholzer, 2001) to as much as 1300 EJ/year (IEA, 2001) to 2900 EJ/year (Obersteiner *et al.*, 2002; Hall and Rosillio-Calle, 1998). Because global demand for food is also expected to double over the next 50 years (Fedoroff and Cohen, 1999), increased biofuel production competes with agricultural land needed for food production.

In this paper we present a methodology for incorporating biomass production technologies into a Computable General Equilibrium (CGE) model. A key strength of CGE models is their ability to model economy-wide effects of policies and other external shocks, rather than just individual markets or sectors. We integrate biomass production technologies and competition for land into the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005), which is a computable general equilibrium model of the economy that has been widely used to study climate change policy. We apply the model to estimate biomass production in different scenarios of greenhouse gas emissions abatement developed by the U.S. Climate Change Science Program (CCSP, 2006). Competition for labor, capital, land, and other resources in the economy is represented in the model.

The paper is organized in the following way. In the next section we describe biomass energy production. Section 3 presents the changes in the EPPA model structure, which we have made to incorporate bioenergy production technologies and competition for land. In Section 4 we examine several scenarios where greenhouse gas emissions are controlled or not, and show the impacts on biomass production, land prices, and the agricultural sector in the USA. Section 5 concludes.

2. BIOMASS ENERGY TECHNOLOGIES

There are several ways biomass is or can be used for energy production. Currently, most biomass is used in the form of woodfuel and manure for cooking and heating. Out of 39 EJ of traditional biomass use in 2002, 21 EJ is consumed in the form of woodfuel, and the rest is from manure, waste and agriculture residues (Smeets and Faaij, 2007). In our paper we do not discuss the traditional use of biomass and focus on so called "modern" and "advanced" biomass energy technologies for transportation fuel and electricity. Liquid and gaseous transport fuels derived from a range of biomass sources are technically feasible. They include methanol, ethanol, di-methyl esters, pyrolytic oil, Fischer-Tropsch gasoline and distillate, and biodiesel from vegetable oil crops (IPCC, 2001). Currently, the largest sources of commercially produced ethanol are from sugar cane in Brazil and from corn in the USA. Biodiesel is produced from rapeseed in Europe. In most cases, current biofuel production is subject to government support and subsidies. In the USA, ethanol is used mostly as an oxygenating fuel additive to reduce carbon monoxide emissions to meet environmental standards. Thus, it is not competing directly with gasoline on the basis of its energy content. As for other uses of biomass, crop and wood residues, animal manures and industrial organic wastes are currently used to generate biogas. Animal fats can also be converted into biodiesel.

Energy yield from different biomass sources can vary substantially. Vegetable oil crops have a relatively low energy yields (40-80 GJ/ha/year) compared with crops grown for cellulose or starch/sugar (200-300 GJ/ha/year). According to IPCC (2001), high yielding short rotation forest crops or C4 plants (*e.g.*, sugar cane or sorghum) can give stored energy equivalent of over 400 GJ/ha/year.

Woody crops are another alternative. The IPCC (2001) reports a commercial plot in Sweden with a yield of 4.2 odt/ha/year, and anticipates that with better technologies, management and experience the yield from woody crops can be up to 10 odt/ha/year. Using the number for a higher heating value (20 GJ/odt) that Smeets and Faaij (2007) used in their study of bioenergy potential from forestry, we can estimate a potential of 84-200 GJ/ha/year yield for woody biomass.

Hybrid poplar, willow, and bamboo are some of the quick-growing trees and grasses that may serve as the fuel source for a biomass power plant, because of the high amount of lignins, a glue-like binder, present in their structures, which are largely composed of cellulose. Such so-called “lignocellulose” biomass sources can potentially be converted into ethanol via fermentation or into a liquid fuel via a high-temperature process.

Land that is needed to grow energy crops competes with land used for food and wood production unless surplus land is available. For example, Smeets and Faaij (2007) estimate a global theoretical potential of biomass from forestry in 2050 as 112 EJ/year. They reduce this number to 71 EJ/year after considering demand for wood production for other than bioenergy use. The number is decreased further to 15 EJ/year when economic considerations are included into their analysis. In the study of biodiesel use in Europe, Frondel and Peters (2007) found that to meet the EU target for biofuels 11.2 Mha are required in 2010, which is 13.6% of total arable land in the EU25. An IEA (2003) study estimates that replacing 10% of fossil fuels by bioenergy in 2020 would require 38% of total acreage in the EU15. These analyses, while providing useful benchmarks, typically take market conditions as given, whereas prices and markets will change in the future and will depend on, for example, the existence of greenhouse gas mitigation policies that could create additional incentives for biofuels production.

Table 1 provides a rough estimate of a global potential for energy from biomass based on the total land area. IPCC (2001) used an average energy yield of 300 GJ/ha/year for its projection of a technical energy potential from biomass by 2050. The area not suitable for cultivation is about half of the total Earth land area of 15.12 Gha and it includes tropical savannas, deserts and semideserts, tundra, and wetlands. Using the numbers for converting area in hectares into energy yield, we estimate the global potential of around 2100 EJ/year from biomass. One can increase or decrease this estimate by including or excluding different land types from the calculation. Assuming a conversion efficiency of 40% from biomass to the final liquid energy product, we estimate a potential of 840 EJ/year of liquid energy product from biomass. **Table 2** presents a similar calculation for the USA, where a potential for a dry bioenergy is about 200 EJ/year, and for a potential for a liquid fuel from biomass is about 80 EJ/year. Note that these are maximum

Table 1. World Land Area and a Potential for Energy from Biomass.

	Area (Gha)	**max dry bioenergy** (EJ)	**max liquid bioenergy** (EJ)
Tropical Forests	1.76	528	211.2
Temperate Forests	1.04	312	124.8
Boreal forests	1.37	411	164.4
Tropical Savannas	2.25		0
Temperate grassland	1.25	375	150
Deserts and Semideserts	4.55		0
Tundra	0.95		0
Wetlands	0.35		0
Croplands	1.6	480	192
Total	15.12	2106	842.4

Source: area (IPCC, 2000); assumptions about area to energy conversion: 15 odt/ha/year and 20 GJ/odt (IPCC, 2001); assumption for conversion efficiency from biomass to liquid energy product: 40%.

Table 2. USA Land Area and a Potential for Energy from Biomass.

	Area (Gha)	**Area** (billion acres)	**max dry bioenergy** (EJ)	**max liquid bioenergy** (EJ)
Cropland	0.177	0.442	53.0	21.2
Grassland	0.235	0.587	70.4	28.2
Forest	0.260	0.651	78.1	31.2
Parks, etc	0.119	0.297		
Urban	0.024	0.060		
Deserts, Wetland, etc	0.091	0.228		
Total	0.906	2.265	201.6	80.6

Source: area (USDA, 2005); assumptions about area to energy conversion: 15 odt/ha/year and 20 GJ/odt (IPCC, 2001); assumption for conversion efficiency from biomass to liquid energy product: 40%.

potential estimates that assume that all land that currently is used for food, livestock, and wood production would be used for biomass production.

A recent study by the U.S. Government (CCSP, 2006) projects an increase in the global energy use from about 400 EJ/year in 2000 to 700-1000 EJ/year in 2050, and to 1275-1500 EJ/year in 2100. The corresponding numbers for the USA are about 100 EJ/year in 2000, 120-170 EJ/year in 2050, and 110-220 EJ/year in 2100. These numbers suggest that energy from biomass alone would not be able to satisfy global needs even if all land is converted to biomass production, unless a major breakthrough in technology occurs.

Concerns about national energy security and mitigation of CO_2 have generated much interest in biofuels, although a recent cost-benefit study (Hill *et al.*, 2006) has found that even if all of the U.S. production of corn and soybean is dedicated to biofuels, this supply would meet only 12% and 6% of the U.S. demand for gasoline and diesel, respectively. And other work has shown that the climate benefit of this fuel, using current production techniques, is limited because of the fossil fuel used in the production of the crop and processing of biomass (Brinkman *et al.*, 2006). Advanced synfuel hydrocarbons or cellulosic ethanol produced from biomass could provide much greater supplies of fuel and environmental benefits than current technologies. Current studies thus raise a number of issues and guide the direction of our representation of biofuels in a CGE model to estimate economy-wide effects of different policies, which we discuss in more detail in the next Section.

3. BIOMASS ENERGY TECHNOLOGIES IN EPPA

The MIT Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic multi-regional computable general equilibrium (CGE) model of the world economy (Paltsev *et al.*, 2005). EPPA is build on the GTAP data set, which accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flows (Hertel, 1997; Dimaranan and McDougall, 2002). Besides the GTAP data set, EPPA uses additional data for greenhouse gas (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) and urban gas (SO_2, NO_x, black carbon, organic carbon, NH_3, CO, VOC) emissions. For use in EPPA the GTAP dataset is aggregated into the 16 regions and 10 sectors shown in **Table 3**. The base year of the EPPA model is 1997. From 2000 onward it is solved recursively at 5-year intervals.

Table 3. Regions and Sectors in the EPPA4 Model.

Country/Region	Sectors
Annex B	***Non-Energy***
United States (USA)	Agriculture (AGRI)
Canada (CAN)	Services (SERV)
Japan (JPN)	Energy Intensive products (EINT)
European Union+[a] (EUR)	Other Industries products (OTHR)
Australia/New Zealand (ANZ)	Industrial Transportation (TRAN)
Former Soviet Union (FSU)	Household Transportation (HTRN)
Eastern Europe[b] (EET)	***Energy***
Non-Annex B	Coal (COAL)
India (IND)	Crude Oil (OIL)
China (CHN)	Refined Oil (ROIL)
Indonesia (IDZ)	Natural Gas (GAS)
Higher Income East Asia[c] (ASI)	Electric: Fossil (ELEC)
Mexico (MEX)	Electric: Hydro (HYDR)
Central & South America (LAM)	Electric: Nuclear (NUCL)
Middle East (MES)	***Advanced Energy Technologies***
Africa (AFR)	Electric: Biomass (BELE)
Rest of World[d] (ROW)	Electric: Natural Gas Combined Cycle (NGCC)
	Electric: NGCC with Sequestration (NGCAP)
	Electric: Integrated Coal Gasification with Combined Cycle & Sequestration (IGCAP)
	Electric: Solar and Wind (SOLW)
	Liquid fuel from biomass (BOIL)
	Oil from Shale (SYNO)
	Synthetic Gas from Coal (SYNG)

[a] The European Union (EU-15) plus countries of the European Free Trade Area (Norway, Switzerland, Iceland).
[b] Hungary, Poland, Bulgaria, Czech Republic, Romania, Slovakia, Slovenia.
[c] South Korea, Malaysia, Philippines, Singapore, Taiwan, Thailand.
[d] All countries not included elsewhere: Turkey, and mostly Asian countries.

The EPPA model production and consumption sectors are represented by nested Constant Elasticity of Substitution (CES) production functions (or the Cobb-Douglas and Leontief special cases of the CES). The model is written in GAMS-MPSGE (Rutherford, 1995). It has been used in a wide variety of policy applications (*e.g*., Jacoby *et al.*, 1997; Reilly *et al.*, 1999; Paltsev *et al.*, 2003; Babiker *et al.*, 2003; Reilly and Paltsev, 2006; CCSP, 2006).

Because of the focus on climate policy, the EPPA model further disaggregates the GTAP data for energy supply technologies and includes a number of energy supply technologies that were not in widespread use in 1997 but could take market share in the future under changed energy price or climate policy conditions. Bottom-up engineering details are incorporated in EPPA in the representation of these alternative energy supply technologies.

We introduce two technologies that use biomass: electricity production from biomass and a liquid fuel production from biomass. Both use land and a combination of capital, labor and other inputs. They compete for land with agricultural sectors of the economy. These technologies endogenously enter if and when they become economically competitive with existing technologies. Competitiveness of different technologies depends on the endogenously determined prices for all inputs, as those prices depend on depletion of resources, climate policy, and other forces driving economic growth such as the savings, investment, energy-efficiency improvements, and the productivity of labor.

The production structures for biomass technologies are shown in **Figure 1**. Production of liquid fuel from biomass (panel *a*) uses capital, labor, and intermediate inputs from the Other Industries (OTHR) sector. Production of electricity from biomass (panel *b*) has a very similar production structure, except that it includes an additional fixed factor to slow initial penetration as described in more detail in McFarland *et al.* (2004). Land is modeled as a non-depletable resource whose productivity is augmented exogenously. Note that the production of the biomass and the conversion of the biomass to fuel or electricity are collapsed into a single nest (*i.e.*, the capital and labor needed for both growing and converting the biomass to a final fuel are combined). These are parameterized to represent a conversion efficiency of 40% from biomass to the final energy product. This conversion efficiency also assumes that process energy needed for biofuel production is from biomass.

Table 4 presents mark-ups and input shares for Bio-Oil and Bio-Electricity technologies. By convention, we set input shares in each technology so that they sum to 1.0. We then separately identify a multiplicative mark-up factor that describes the cost of the advanced technology relative to the existing technology against which it competes in the base year. This markup is a multiplier for all inputs. For example, the mark-up of the Bio-Oil technology in the USA region is 2.1, implying that this technology would be economically competitive at a refined oil price that is 2.1 times that in the reference year (1997) *if* there were no changes in the price of inputs used either in refined oil production or in production of liquid fuel from biomass. As with conventional technologies, the ability to substitute between inputs in response to changes in relative prices is controlled by the elasticities of substitution, which are given in **Table 5**.

As identified in the previous section, corn and soybean based biofuel liquid production potential is relatively limited, and current biomass production processes in the USA (*e.g.*, ethanol from corn) often use fossil energy thus releasing nearly as much CO_2 as is offset when the ethanol is used to replace gasoline. Potential production from these sources is too limited to ever

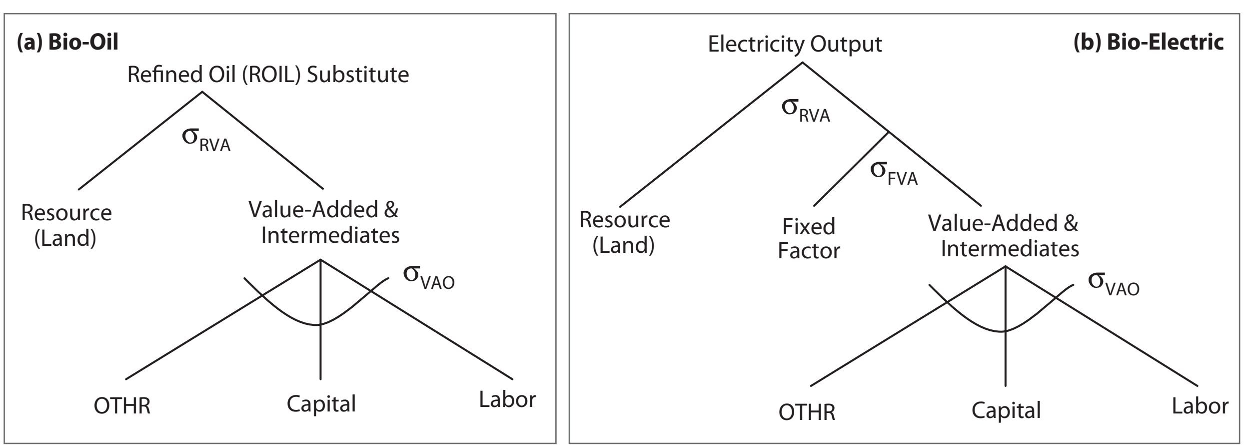

Figure 1. Structure of Biotechnology Production Functions for **(a)** Bio-Oil and **(b)** Bio-Electric.

Table 4. Mark-ups and Input Shares for Bio-oil and Bio-electric Technologies.

		Input Shares				
Supply Technology	Mark-up Factor	Resource	OTHR	Capital	Labor	Fixed Factor
Bio-oil	2.1	0.10	0.18	0.58	0.14	--
Bio-electric	1.4-2.0	0.19	0.18	0.44	0.14	0.05

Table 5. Reference Values for Elasticities in Bio-Oil and Bio-Electric Technologies.

σ_{RVA}	Resource-Value Added/Other	0.3	Bio-Electric
		0.1	Bio-Oil
σ_{FVA}	Fixed Factor-Value Added/Other	0.4	Bio-Electricity
σ_{VAO}	Labor-Capital-OTHR	1.0	Bio-Oil & Bio-Electricity

play a role much beyond that of producing enough ethanol to serve as a oxygenating additive to gasoline in the USA. Our modeling focus is thus to represent advanced technologies that can make use of a broader biomass feedstock, thereby achieving levels of production that can make a more substantial contribution to energy needs. For our purposes, there is also little reason to represent CO_2-intensive production processes because in scenarios where carbon is priced, their cost would escalate with the carbon price just as would the price of conventional refined oil (ROIL), and thus it would never be competitive. An alternative strategy is to introduce several competing biomass energy technologies with different cost specifications and technology specifications. As a first step, our approach is to specify a technology that is likely to dominate others over the longer term. These considerations drive our parameterization of the bioenergy technologies.

We considered early estimates of global resource potential and economics (Edmonds and Reilly, 1985) and recent reviews of potential (Moreira, 2004; Berndes *et al.*, 2003) and the economics of liquid fuels (Hamelinck *et al.,* 2005) and bio-electricity (International Energy Agency, 1997). Regarding cost, Hamelinck *et al.* (2005), estimate costs of lignocellusic conversion of ethanol of 8.7 to 13 €/GJ compared with 8 to 12 and eventually 5 to 7 €/GJ for methanol production from biomass. They compare these to before tax costs of gasoline production of 4 to 6 €/GJ. Our estimated mark-up of 2.1 is thus consistent with the lower end of the near- and mid-term costs for ethanol or methanol. We parameterize land requirements per unit of biofuel produced to be consistent with the 300 GJ/ha/year.

The CGE framework measures all inputs in monetary units. If we wish to inform our parameterization of input shares, land productivity, and conversion efficiencies from agro-engineering studies we must translate them into units used in the CGE model. Thus, to get from the 300 GJ/ha/year we need an estimate of the land price. We assume the productivity rate is for "average" cropland, and thus use the average USA cropland price and our assumption of 40% efficiency of conversion to estimate the initial value share of land in biofuel production. The amount of biofuel liquid produced in GJ must then compete with our ROIL in the base year with input shares adding to 1.0, for which we have the GTAP supplemental physical energy accounts. This ensures that the physical energy produced by the Bio-Oil technology is equal to the ROIL product for which it is a perfectly competitive good. The mark-up multipliers on other inputs in the production technology then produce a final cost of the biofuel technology reflecting existing cost studies of biofuels relative to gasoline. The same approach is used for Bio-Electricity where the comparison of energy output is with the conventional electricity sector for which Bio-Electricity produces a perfectly competitive substitute.

The same calculations that allow us to parameterize the production technology then allow us to back-out estimates of physical land used in bioenergy production. An important caveat to this result is that the quantity of land in hectares should be considered as an "average cropland equivalent." Obviously, land quality and land prices vary. The National Income and Product Accounting approach that is the basis of CGE data takes the value of different land as an indication of its marginal product. The implication for our CGE model is that when we use a unit of land in monetary terms we are using a comparable productivity unit—an "average cropland equivalent." In reality, this could be more hectares of less productive (less valuable) land or fewer hectares of more productive (more valuable land). By parameterizing bioenergy in this way it implies that productivity of land in terms of GJ/ha/year is directly proportional to the land price as it varies across different land types in the base year. While this is unlikely to be strictly true, as a first approximation it is likely reasonable.

One way to evaluate the reasonableness of this assumption is to consider the levels of bioenergy produced globally, when economic conditions strongly favor production in a model simulation, compared with estimates of global potential in the literature that take into account continued use of land for conventional agricultural purposes. The range of the estimated global biomass production potential is very wide, depending on assumptions of yield, available land that would be allowed to be converted to a biomass crop, and competition with agriculture. Our estimated contribution in reference and policy runs based on the parameterization of biomass production fits within that range.

4. ILLUSTRATIVE SCENARIOS

The EPPA model has been used in a variety of recent policy applications. We draw on two of those to illustrate the modeling of bioenergy in EPPA, and the potential role of biomass as an energy supplier. The first of these applications involves scenarios of atmospheric stabilization of greenhouse gases (GHGs). The second involved investigation of USA GHG mitigation policies that have been proposed in Congressional legislation. These applications allow us to focus both on the global bioenergy potential and on some specific issues with regard to USA bioenergy.

4.1 Atmospheric Stabilization of Greenhouse Gases

To illustrate how the EPPA model performs in terms of bioenergy technologies, we use the reference and four stabilization scenarios employed in the recent U.S. Climate Change Science Program (CCSP, 2006). The four stabilization scenarios were developed so that the increased radiative forcing from greenhouse gases was constrained to no more than 3.4 W/m^2 for Level 1, 4.7 W/m^2 for Level 2, 5.8 W/m^2 for Level 3, and 6.7 W/m^2 for Level 4. These levels were defined as increases above the preindustrial level, so they include the roughly 2.2 W/m^2 increase that has already occurred as of the year 2000. These radiative forcing levels were chosen so that the associated CO_2 concentrations would be roughly 450 ppm, 550 ppm, 650 ppm, and 750 ppm.

In these scenarios we do not consider climate feedbacks. The numbers for biomass represent only the production of biomass energy from the advanced technologies we have represented in EPPA and does not include, for example, the own-use of wood wastes for energy in the forest products industry. Those are implicit in the underlying data in the sense that to the extent the forest product industry uses its own waste for energy, it purchases less commercial energy. Similarly, to the extent that traditional biomass energy is a substantial source of energy in developing countries it implies less purchase of commercial energy.[1] **Figures 2** and **3** present "advanced" biomass production for the world and in the USA across the scenarios. The reference scenario exhibits a strongly growing production of biofuels beginning after the year 2020. Deployment is driven primarily by a world oil price that in the year 2100 is over 4.5 times the

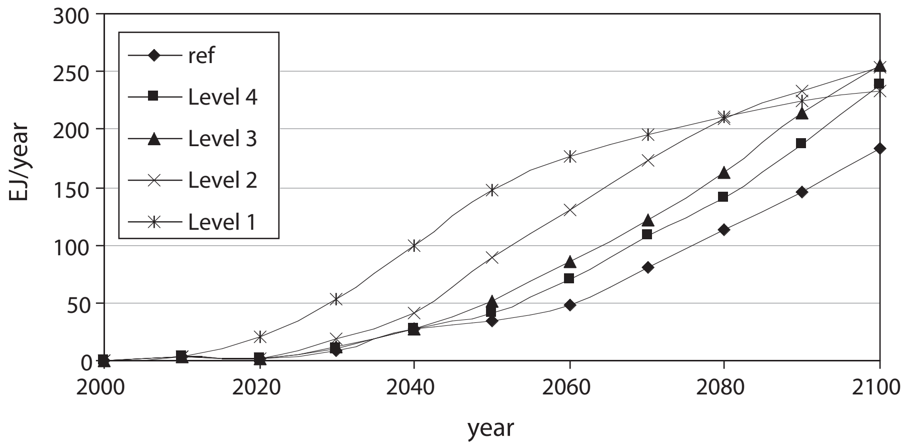

Figure 2. Global Biomass Production across Scenarios.

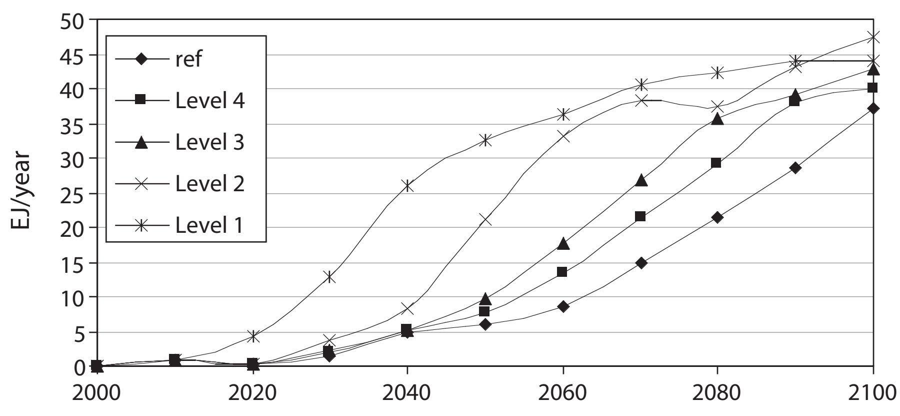

Figure 3. USA Biomass Production across Scenarios.

[1] Developing countries are likely to transition away from this non-commercial biomass use as they become richer, and this is likely one reason why we do not observe rates of energy intensity of GDP improvements in developing countries that we observe in developed countries. The EPPA model accommodates this transition by including lower rates of Autonomous Energy Efficiency Improvement in poorer countries, thus capturing the tendency this would have to increase commercial fuel use without explicitly accounting for non-traditional biomass use.

price in the year 2000. In the stabilization scenarios, global biomass production reaches 250 EJ/year, and the USA biomass production is in the 40-48 EJ/year range by 2100. The types of land are not modeled explicitly in the current version of the model, but using the estimates from Tables 1 and 2 we can conclude that the EPPA model provides a fairly optimistic picture for biomass production, because 250 EJ/year would require about 2 Gha of land and 45 EJ/year would require 0.375 Gha of land. Even if we would assume a more optimistic conversion efficiency of more than 40%, the area of land is still comparable to the current crop area both in the global in the USA cases.

Figures 4 through **6** show the composition of global primary energy for the reference, Level 3, and Level 1 scenarios. Across the stabilization scenarios, the energy system relies more heavily on non-fossil energy sources, and biomass energy plays a major role. Total energy consumption, while still higher than current levels, is lower in stabilization scenarios than in the reference scenarios, and carbon capture and storage (CCS) technologies are widely deployed. While we do not report here electricity production by technology, and so do not see the contribution of Bio-Electricity, we find that the Bio-Electricity technology is rarely if ever used.

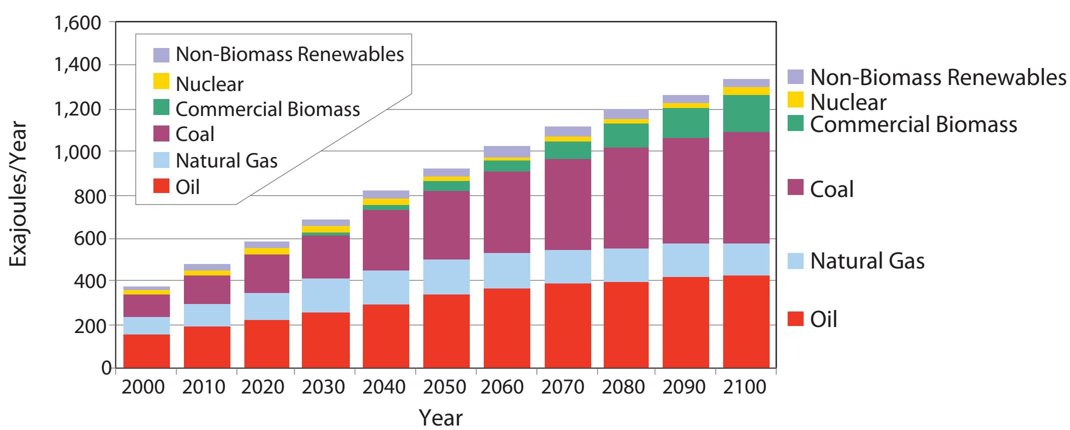

Figure 4. Global Primary Energy Consumption in the reference case.

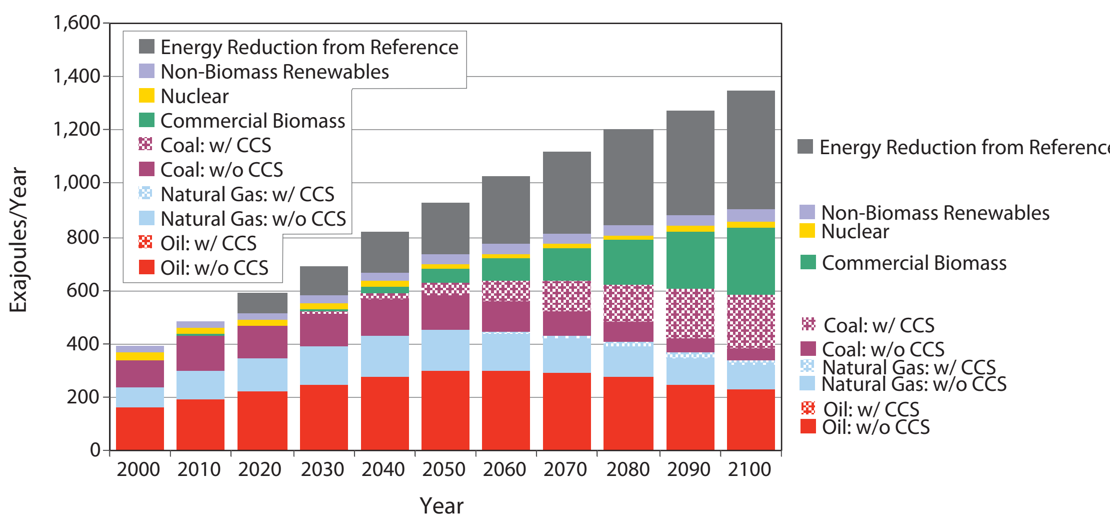

Figure 5. Global Primary Energy in the Level 3 Scenario.

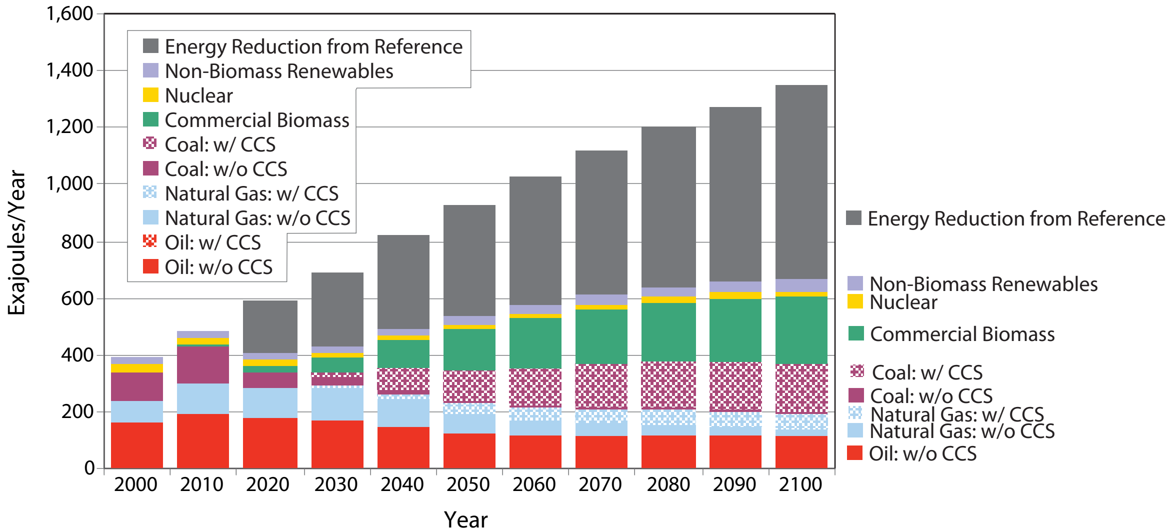

Figure 6. Global Primary Energy in the Level 1 Scenario.

Coal continues to be an inexpensive source of energy for power generation in the reference case and so Bio-Electricity does not compete. In the stabilization scenarios, there are a variety of low carbon and carbon-free generation technologies that out-compete Bio-Electricity. An important reason for this is that the demand for Bio-Oil is so strong because there are no other good low-carbon substitutes for petroleum products used in the transportation sector. As a result, this demand drives up the land price and raises the cost of Bio-Electricity. **Figure 7** present a land price impact in the USA in the Level 2 scenario compared with the reference price for land. Land prices in the USA more than double due to increased biomass demand. Land prices in the Level 1 scenario are actually somewhat lower than in the Level 2 because of overall economic impact.

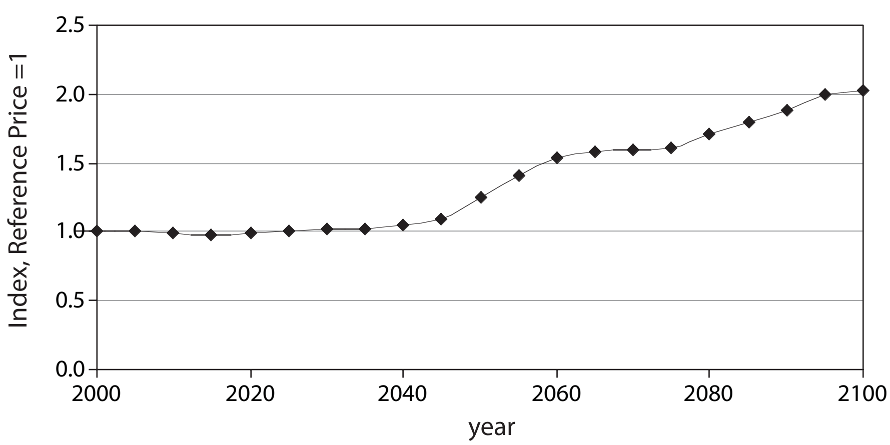

Figure 7. Land Price in USA in the Level 2 Scenario compared with Reference Land Price.

4.2 The potential role of bioenergy in USA greenhouse gas policy

In 2003 Senators McCain and Lieberman introduced cap-and-trade legislation in the USA Senate. For a discussion and analysis see Paltsev *et al.* (2003). Interest in GHG mitigation legislation in the USA Congress has grown substantially since then, and as of 2007 there are several proposals for cap-and-trade systems in the USA including a revised proposal by McCain and Lieberman. Compared with the earlier proposals, these Bills envision much steeper cuts in USA emissions and extend cap-and-trade system through year 2050. Some of these envisioned emissions in the USA are as much as 80% below the 1990 level by 2050. This would be as much as a 91% reduction from the EPPA reference emissions projected in 2050. Such a steep reduction cannot avoid making significant cuts from CO_2 emissions from transportation, which currently accounts for about 33% of USA CO_2 emissions related to fossil fuel combustion (EIA, 2006). While improved efficiency of the vehicle fleet might contribute to reductions, it is hard to imagine sufficient improvements in that regard. Of the contending alternative fuels—hydrogen, electric vehicles, biofuels—the biofuel option appears closest to being technologically ready for commercialization. A more complete discussion and analysis of current Congressional proposals is provided in Paltsev *et al*. (2007). Here we focus on the role of bioenergy under these mitigation scenarios.

To capture the basic features of different proposals, we assume that the policy enters into force in 2012. The initial allowance level is set to the (estimated[2]) USA GHG emissions in 2008 and the annual allowance allocation follows a linear path through 2050 to: (1) 2008 emissions levels; (2) 50% below 1990; and (3) 80% below 1990. Over the 2012 to 2050 period the cumulative allowance allocations under these three scenarios are 287, 203, and 167 billion metric tons (bmt) of CO_2-equivalent (CO_2-e). The EPPA model simulates every 5 years, so the initial year for which the policy is in place in the simulations is 2015. We designate these scenarios with the shorthand labels *287 bmt*, *203 bmt*, and *167 bmt*. We approximate banking of allowances in the USA, as allowed in several of the proposals, by meeting the target with a CO_2-e price path that rises at the rate of interest, assumed to be 4%. We assume that other developed countries pursue a policy whereby their emissions also fall to 50% below 1990 levels by 2050, and a policy whereby all other regions return to (our projected) 2015 level of emissions in 2025, holding at that level until 2035 when the emissions cap drops to their year-2000 level of GHG emissions. We do not allow international emissions trading but we do simulate economy-wide trading among greenhouse gases at their Global Warming Potential (GWP) value. All prices are thus CO_2-equivalent prices. The carbon dioxide prices required to meet these policy targets in the initial projection year (2015) are \$18, \$41, and \$53/t CO_2-e for the *287, 203*, and *167 bmt* cases, respectively.

In one set of scenarios we allow unrestricted trade in biofuels. We find significant amounts of biofuel use in the USA in the more stringent scenarios but that nearly all of it is imported. There are currently tariffs on biofuel import into the USA, and one of the reasons biomass is of interest in the USA is because it could be produced from domestic resources. We thus consider a separate set of scenarios where all biofuel use in the USA (and in other regions of the world) must be produced domestically. We designate these with the extension *NobioTR* (for no biofuel trade).

[2] We estimate 2008 emissions by extrapolating from the most recent USA inventory for 2005 at the 1% per year growth in GHG emissions observed over the past decade.

Turning to the specific simulation results, we find that USA biofuel use is substantial in the 203 bmt and 167 bmt cases, rising to 30 to 35 EJ and in the core cases (**Figure 8**, panel a). The 287 bmt case results in very little USA biofuels consumption—less than 1 EJ in any year, and so we do not show it in the Figure 8. World liquid biofuel use is substantial in all 3 cases, reaching 100 to 120 EJ, because the ROW (rest of the world) region in the EPPA model is pursuing the same strong GHG policy even as we vary the policy in the USA. Thus, the main difference in the world total is the changes in biofuels use in the USA. If the USA pursued the *287 bmt* case and the rest of the world did nothing, there would be substantial biofuels use in the USA. However, when the rest of the world pursues a GHG mitigation policy the USA cannot compete in the biofuels market. When we restrict biofuel use only to domestically produced, we find somewhat lower biofuels use in the USA and in the total for the world (Figure 8, panel b). However, biofuel use, and hence production, in the USA is substantial falling in the 25 to 30 EJ range by the end of the period rather than the 30 to 35 EJ. Biofuel has substantially displaced petroleum products accounting for nearly 55% of all liquid fuels in the USA. Based on calculations from Table 2, this would require about 30% of all USA crop, grass, and forestland (over 500 million acres of land).

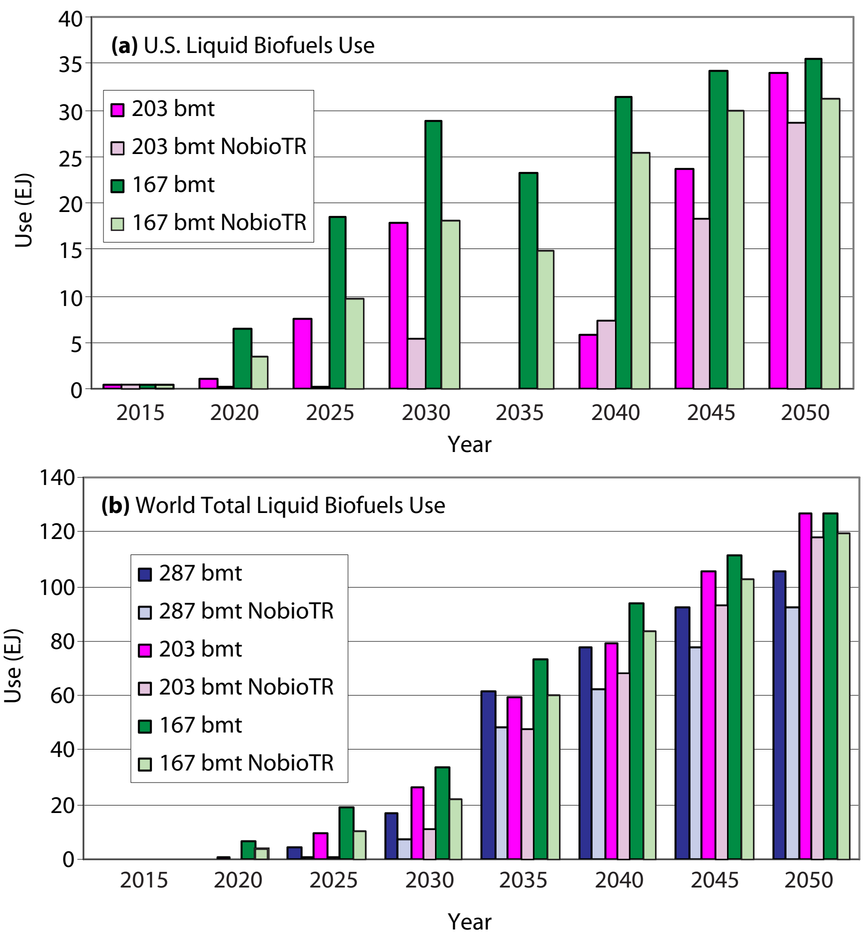

Figure 8. Liquid biofuel use, with and without international trade in biofuels: **(a)** USA, **(b)** world total.

How is that possible, and what are the implications for the broader agricultural sector? **Figure 9** illustrates one of the important implications of substantial biofuels production, focusing on just the *167 bmt* case. The USA is currently a substantial net agricultural exporter, and under the EPPA reference without GHG policy this is projected to continue. In the *167 bmt* case, USA net agricultural exports are projected to double compared with a reference case without any policy. As other regions expand ethanol production, they import more agricultural goods and thus USA net exports grow. The significant effect of forcing biofuels to be produced domestically under a stringent climate policy is significant reduction in USA agricultural production. Instead of the USA being a significant net exporter of agricultural commodities, it becomes a large net importer. Whereas net exports today are on the order of $20 billion, by 2050 in the *167 bmt NobioTR* case the USA grows to be a net importer of nearly $80 billion of agricultural commodities. The agricultural sector in the EPPA model is highly aggregated—a single sector includes crops, livestock, and forestry. As a result, one should not put too much stock in the absolute value of net exports in the reference—it could be higher or lower depending on how agricultural productivity advances in the USA relative to other regions of the world. However, if about 25 EJ of ethanol must be produced in the USA (requiring about 500 million acres of land), it is nearly inevitable that this would lead to the USA becoming a substantial agricultural importer.

Several other critical aspects of this level of biofuels production are worth pointing out. Following the design of USA policies under consideration, as well as policy design discussion abroad such as the European emissions trading scheme or under the Kyoto Protocol, we have not extended the cap-and-trade system to cover land-use emissions (see Reilly and Asadoorian, 2007). If included at all, land use is often covered under a crediting system. However, as shown by McCarl and Reilly (2006), except for quite low carbon prices, the economics of biofuels tends to dominate the economics of carbon sequestration in soils. The implication is that at the level of biofuels demand simulated here, there would be very little incentive to protect carbon in the soils and vegetation through a credit system. Landowners would instead tend to convert land to biofuels or more intense cropping. Whether the biofuels themselves are produced on existing

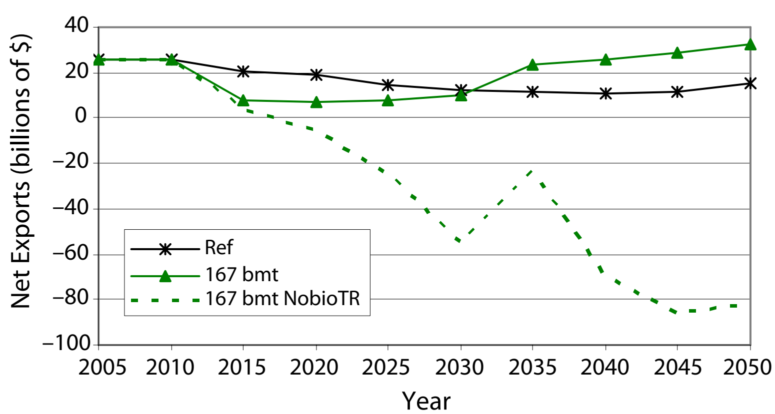

Figure 9. Net agricultural exports in the *167 bmt* case, with and without biofuels trading.

cropland or not, the overall need for cropland would require significant conversion of land from less intensively managed grass and forestland. This initial disruption would lead to significant carbon dioxide release from soils and vegetation. If mature, virgin forests are converted it can take decades of biofuels production to make up for the initial carbon loss. Whether this land is converted in the USA or somewhere abroad, it is likely to contribute substantial carbon emissions, negating the savings from reduced fossil energy use. Thus, one of the most serious issues raised in this analysis is the need to expand a cap-and-trade system to include land-use change emissions, and to be doubly concerned about leakage from reductions in the USA through biofuels imports unless mitigation policies abroad *that include land-use emissions* are in place.

5. CONCLUSION

Two technologies which use biomass—electricity production from biomass and a liquid fuel from biomass—are introduced into the EPPA model to estimate the biomass energy use in different economic scenarios. Biomass technologies use land and a combination of capital, labor and other inputs. They compete for land with other agricultural sectors. Our approach represents biomass production, transportation, and conversion in a single production function that we can benchmark to agro-engineering data on biomass productivity per hectare and the cost and conversion efficiency of bio-liquids and biomass-based electricity. A more structurally realistic treatment might represent explicitly growing a crop for biomass (or several different crops), transportation of biomass to a processing/conversion facility, conversion, and different end-use equipment requirements. In our approach, we have no direct conventional energy inputs in this process. We assume that the majority of needed energy (for harvesting/planting crop; transporting to conversion facility, and in conversion) is provided by biomass itself, thus we assume a relatively low (40%) conversion efficiency. Indirectly, other energy is used in production of other industry/capital goods production that are inputs to bioenergy production. We thus have no carbon emissions from bioenergy production itself. Implicitly, we assume that biomass crops are grown in a "sustainable" manner in the sense that CO_2 released, when the bioenergy is produced and used, is taken-up by the next biomass crop. Given the potential scale of the bioenergy industry in the scenarios we considered, this is unlikely to be a realistic assumption. Further modeling is needed to investigate the potential carbon release from large-scale land conversions that would be needed to support a substantial bioenergy industry.

We test our representation of biomass technologies in different scenarios. Global increase in biomass production in a reference scenario (with no climate change policy) is about 30 EJ/year by 2050 and about 180 EJ/year by 2100. This deployment is driven primarily by a world oil price that in the year 2100 is over 4.5 times the price in the year 2000. Different scenarios of stabilization of greenhouse gases increase the global biomass production to 40-150 EJ/year by 2050 and 220-250 EJ/year by 2100. The area of land required to produce 180-250 EJ/year is about 2Gha, an equivalent of the current global total crop area. The magnitude and geographical distribution of climate-induced changes may affect human's ability to expand food production in order to feed growing population. In addition to food production, consumption behavior might also shift in the future with unexpected consequences. In another set of policy experiments we examine the potential role of bioenergy in contributing to USA GHG mitigation efforts. We find a substantial role for bioenergy but the USA, at least in our representation, imports biofuels rather than grow them domestically. USA agriculture still expands because the need for land for biofuels production abroad means that agricultural production is reduced abroad, increasing USA agricultural exports. If we restrict USA biofuels to those produced domestically, as much as 500 million acres of land would be required in the USA for biofuels production, which would be enough to supply about 55% of the country's liquid fuel requirements. The result would be that the USA would need to become a substantial agricultural importer. This suggests that the idea that biomass energy represents a significant domestic energy resource in the USA is misplaced. If the USA were to actually produce a substantial amount of biofuels domestically, through polices that spurred its use but that prevented imports, instead of relying on oil imports the country would need to rely on food imports. The overall conclusion is that the scale of energy use in the USA and the world relative to biomass potential is so large that a biofuel industry that was supplying a substantial share of liquid fuel demand would have very significant effects on land use and conventional agricultural markets.

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