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The Impact of Oil Prices on Bioenergy, Emissions and Land Use

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This reprint is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn and John M. Reilly,
Joint Program Co-Directors

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The impact of oil prices on bioenergy, emissions and land use

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ABSTRACT

We evaluate how alternative future oil prices will influence the penetration of biofuels, energy production, greenhouse gas (GHG) emissions, land use and other outcomes. Our analysis employs a global economy wide model and simulates alternative oil prices out to 2050 with and without a price on GHG emissions. In one case considered, based on estimates of available resources, technological progress and energy demand, the reference oil price rises to $124 by 2050. Other cases separately consider constant reference oil prices of $50, $75 and $100, which are targeted by adjusting the quantity of oil resources. In our simulations, higher oil prices lead to more biofuel production, more land being used for bioenergy crops, and fewer GHG emissions. Reducing oil resources to simulate higher oil prices has a strong income effect, so decreased food demand under higher oil prices results in an increase in land allocated to natural forests. We also find that introducing a carbon price reduces the differences in oil use and GHG emissions across oil price cases.

1. Introduction

At the recent 21st United Nations Conference of the Parties (COP21) in Paris, 188 countries committed to reduce future greenhouse gas (GHG) emissions. Meeting these targets will, among other changes, require replacing energy from fossil fuels with low-carbon forms of energy, including electricity from wind and solar and energy from biomass. Energy stored in biomass can be converted to many forms of final energy, including biofuels, bioelectricity, and bioheat.

Several studies have examined the impacts of bioenergy production on GHG emissions, land use, food prices and/or other outcomes, either by considering bioenergy mandates (e.g., Rahdar et al., 2014; Searchinger et al., 2008; Timilsina et al., 2012; Treesilvattanakul et al., 2014; Wise et al., 2014) or simulating a global carbon price (e.g., Calvin et al., 2014; Reilly et al., 2012; Winchester and Reilly, 2015). The general conclusion from this literature is that biofuels could play a major role in reducing GHG emissions, especially in the transportation sector, without large adverse effects on the food sector. However, although the penetration of each form of bioenergy will depend on, among other factors, policy incentives and the costs of each bioenergy pathway relative to energy from other sources, these studies are based on a single oil price projection. Moreover, by influencing the production of biofuels, the oil price will also affect outcomes for other forms of bioenergy – either because they use the same feedstock or through competition for land – and non-biomass energy via energy market interactions.

The price of oil is sensitive to economic and geopolitical events (Bastianin et al., 2011) and can be difficult to forecast (Morrell and Dray, 2009). Furthermore, oil price projections can be subject to large revisions in response to recent changes in current oil prices. For example, in 2007 the US Energy Information Administration's reference oil price projection for 2030, in 2010 dollars per barrel (bbl), was $59.12 (EIA, 2007) and, following a spike in oil prices in July 2008, was revised to $137.17 in 2009 (EIA, 2009). Additionally, although publically-available oil price projections typically follow an upward trend – for example, Haugom et al. (2016) estimate annual oil price increases of between 1.4% and 12.5% in coming decades – sharp price increases have typically induced demand and supply responses that have led to periods of falling oil prices (Zycher, 2013). Related to this issue, Huntington (1994) notes that following sharp increases in oil prices in 1979–80 many oil experts expected steadily rising oil prices whereas nominal oil prices actually decreased.

Several previous studies have considered the global impact of oil prices on GHG emissions and bioenergy outcomes. Timilsina (2015) conducts an economy-wide analysis of alternative oil prices out to 2020, but he does not consider second generation biofuel technologies or the use of biomass for heat and electricity, and he does not report changes in GHG emissions or land use. Calvin et al. (2016) explore the impact of different scenarios of fossil fuel resource bases on future

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carbon emissions and bioenergy use using the Global Change Assessment Model (GCAM).

This study complements the existing literature by evaluating how alternative future oil prices will influence the penetration of bioenergy, energy production, GHG emissions, land use and other outcomes. Our analysis employs a global energy-economic model and simulates a global carbon price chosen to isolate the interplay between fossil fuel prices, bioenergy and emissions out to 2050. In some scenarios, oil prices are held constant – at $50, $75 and $100 per bbl – while in other scenarios oil prices are determined by estimates of available resources, technological progress and energy demand.

This paper has four further sections. The next section outlines our modeling framework. Section 3 details the scenarios considered in our analysis. Results from our modeling exercises are presented and discussed in Section 4. The final section concludes.

2. A global model of economic activity, energy and emissions

Our study employs the MIT Economic Projection and Policy Analysis (EPPA) model that includes land-use change (Gurgel et al., 2007; Gurgel et al., 2011), a detailed representation of bioenergy (Winchester and Reilly, 2015), and constraints on the expansion of irrigated crop land (Winchester et al., 2016).

2.1. The economic projection and policy analysis model

The EPPA model is an applied general equilibrium model of global economic activity, energy production and GHG emissions with regional and sectoral detail. The model is recursive dynamic and is solved through time in five-year increments. Aggregation in the extended version of the EPPA model used in our analysis is summarized in Table 1. The model divides the global economy into 16 regions, some of which represent individual countries (e.g., the US and China) while other regions include an aggregation of nations (e.g., Dynamic Asia and Africa).

For each region, the model represents 14 broad production sectors: five energy sectors (coal, crude oil, refined oil, gas and electricity), three agricultural sectors (crops, livestock and forestry), and six other non-energy sectors (energy-intensive industry, commercial transportation, private transportation, food products, services and other industries). For some sectors, there are multiple technologies to produce the same commodity. For example, crude oil can be produced both from underground reservoirs and unconventional resources, such as oil from sand. Likewise, refined oil can be produced from crude oil or from biomass, and there are several technologies for generating electricity. Whether or not a particular technology operates is determined endogenously in the model and depends on the basic input requirements specified for each technology, the prices of these inputs as endogenously determined in each time period, and the output price when compared against the reference technologies with which it competes. For example, electricity from coal with carbon capture and storage (CCS) will not be profitable in the absence of policy incentives, but may operate under a carbon price. Similarly, many biofuel technologies are more expensive than petroleum-based fuels but can be forced to operate through policy mandates and/or a sufficiently high carbon price.

The representation of bioenergy in the model developed by Winchester and Reilly (2015) includes several biomass-to-energy pathways. Bioenergy feedstocks and technologies in the model include (1) seven first generation biofuel crops and conversion technologies; (2) a representative energy grass and a representative woody crop; (3) agricultural and forestry residues; (4) lignocellulosic (LC) ethanol via a biochemical process and LC drop-in fuel using a thermochemical process, both of 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. The model also explicitly represents bioenergy co-products (e.g. distillers' dry grains and surplus electricity), international trade in biofuels, and limits on the blending of ethanol with gasoline. We employ the 'base' blending case specified by Winchester and Reilly (2015), where the maximum proportion of ethanol that can be blended with gasolines rises rapidly beginning in 2025. As with other technologies, whether or not each bioenergy technology operates is determined endogenously in the model and depends on relative costs and policies. Using this framework, Winchester and Reilly (2015) find that LC ethanol becomes a key competitor for refined oil from crude oil. Guided by estimates from BP (2015), the cost of LC ethanol in our analysis, in 2010 dollars per gasoline equivalent gallon, falls through time and from $7.10 in 2015 to $2.63 in 2050. For each bioenergy technology, conversion costs are the same in all regions but feedstock costs vary regionally according to differences in yields and land rents.

Factors of production include labor, capital, seven land types, and resources specific to energy extraction and production of some energy technologies. The labor endowment is set exogenously in each region according to period-by-period population projections, and the stock of capital in each period adjusts according to depreciation and investment in the previous period. In a 'base' scenario (usually a reference scenario), labor productivity in each region and each period is chosen endogenously to calibrate to exogenous GDP estimates. In other scenarios, labor productivity parameters are set equal to those determined in the

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

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

base case and GDP is endogenous. One land type can be converted into another land type following the land-use change specification set out by Gurgel et al. (2007) and Melillo et al. (2009) and, for conversion of rainfed crop land to irrigated crop land, the representation of irrigation costs and water constraints developed by Winchester et al. (2016). Technology-specific factors are used to capture penetration and adoption constraints for low carbon technologies and, as outlined by Morris et al. (2014), depend on production in previous periods and other factors.

Production for each commodity is represented by nested constant elasticity of substitution (CES) functions that produce output by combining primary factors (labor, capital, land, and energy resources) and intermediate inputs. The nesting structure and elasticities of substitution for each technology are chosen to reflect physical requirements and key tradeoffs among inputs in each sector. For example, the sectoral production functions allow producers to substitute between primary energy commodities and, to capture price induced changes in energy efficiency, to substitute between aggregate energy and other inputs.

Demand functions for household purchases of goods and services and investment in each region are derived from the utility-maximizing behavior of a representative agent in each region that derives income from the ownership of all factor endowments (capital, labor, and natural resources) in the region. Household final demand includes an explicit representation of household transportation, which is comprised of private transportation (purchases of vehicles and associated goods and services needed to run and maintain them) and purchases of commercial transportation (e.g., transport by buses, taxis and airplanes). There is also a government sector that collects revenue from taxes and purchases goods and services. Government deficits and surpluses are passed to consumers as lump-sum transfers.

All commodities in the model are traded internationally and differentiated by region of origin following the Armington assumption (Armington, 1969), except for crude oil and biofuels, which are considered to be homogenous goods. For each region, the model tracks bilateral exports and imports of differentiated goods, and net imports/exports of homogenous goods. Goods and services used as intermediate inputs and entering final demand in each region are typically composites of domestically produced and imported varieties.

GHG emissions in the model are linked to the use of fossil fuels, land use change, industrial and agricultural activities, and waste handling. GHGs tracked in the model include carbon dioxide (CO_2), methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons and sulfur hexafluoride.

Calibration of the model draws on economic data from Version 7 of the Global Trade Analysis Project (GTAP) database (Narayanan & Walmsley, 2008; Aguiar et al., 2016), population projections from the United Nations Population Division (UN, 2011), and energy data from the International Energy Agency (IEA, 2006 & 2012). Regional economic growth is calibrated to International Monetary Fund (IMF) data (IMF, 2013) through 2015 and GDP projections from 2020 to 2050 are informed by Paltsev et al. (2005) and Gordon (2012). The model is coded using the General Algebraic Modeling System (GAMS) and the Mathematical Programming System for General Equilibrium analysis (MPSGE) modeling language (Rutherford, 1995).

2.2. Fossil fuel production in the EPPA model

Each fossil fuel is produced in the EPPA model by combining a fuel-specific resource and other inputs, as illustrated in Fig. 1. In the non-resource input nest, capital and labor trade off according to the elasticity parameter σ_{K-L}, and the capital-labor aggregate is combined with intermediate inputs in a Leontief nest. Fuel resources are represented as graded resources, where extraction costs rise as resources are depleted. Following Rutherford (2002), the supply response for each fossil fuel is determined by the elasticity of substitution between the fuel resource and other inputs (σ_{K-L}), and the value share of the resource input.

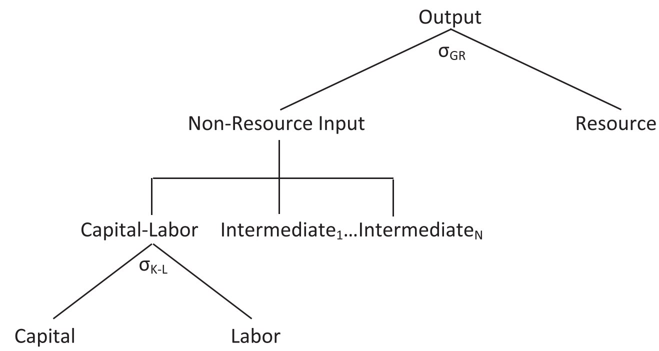

Fig. 1. The production structure for fossil fuel sectors (Coal, Oil and Gas) in the EPPA model. Note: Intermediate inputs potentially include all sectors listed in Table 1.

The price of each fossil fuel in reference simulations in the EPPA model can either be determined endogenously as a result of the supply and demand for fuels, or exogenously set equal to a specified value. For each fossil fuel, the endogenous price method relies on estimating the availability of the fuel-specific resource, which in turn influences the supply response for each fossil fuel. In endogenous price specification, resource availability in a given time period in each region depends on the quantity of the resource used in previous periods and the initial assignment of the resources. In the model, initial endowments of fossil fuel resources are consistent with fossil fuel recoveries that are currently considered economically and technically feasible and an estimate of undiscovered resources. Estimate of fossil resources used in the EPPA model are detailed by Paltsev et al. (2005), Paltsev et al. (2011) and Chen et al. (2011).

When fossil fuel prices are endogenous, fuel prices may either rise or fall over time. For example, increasing energy demand and depletion of the stock of each resource over time will drive increases in fossil fuel prices, while improvements in energy efficiency and economy-wide advances in technology will place downward pressure on these prices.

In the exogenous price method, a predetermined fossil fuel price can be simulated in the model by, in each period, endogenously solving for the quantity of the fuel-specific resource that result in the desired price. As such, the quantity of fossil resources in each period is independent of the initial assignment of the resource and its use in previous periods. In policy simulations for both the endogenous and exogenous fuel price specifications, fossil fuel prices are determined internally in the model based on supply and demand, where supply in each specification is consistent with fossil resources in the relevant reference case.

The two methods for determining fossil fuel prices are compared in Fig. 2, using crude oil as an example. Suppose that, under the endogenous price method in a reference scenario, the quantity of crude oil

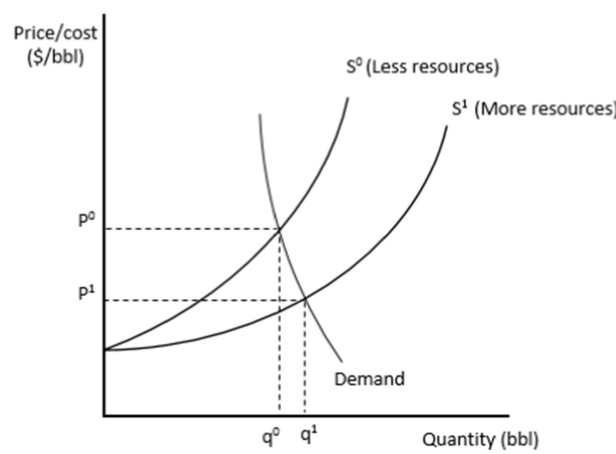

Fig. 2. The relationship between crude oil prices and crude oil resources.

resources available in a given time period results in the supply curve given by S^0. The costs of the most easily accessible resources are represented by the vertical intercept for the supply curve, and the upward slope of the supply curve is consistent with extraction costs rising as more resources are recovered. Given demand for crude oil, the price of crude oil will be p^0 and the quantity traded will be q^0. Under the exogenous price method, a reference scenario with a lower oil price can be simulated by increasing the availability of oil reserves, which would shift the supply to the right and lead to an equilibrium price and quantity for crude oil of, respectively, p^1 and q^1. In policy scenarios corresponding to a reference oil price of p^0, the oil price is determined by the interaction of the demand curve, which may be affected by the policy, and the supply curve S^0. Similarly, in policy scenarios corresponding to a reference price of p^1, the oil price is determined by the intersection between the demand curve and the supply curve S^1.

Table 2
Scenarios considered.

Scenario	Carbon price?*	Crude oil price from 2015 to 2050, 2010$ per bbl
Ref-50	No	Constant at $50
Ref-75	No	Constant at $75
Ref-100	No	Constant at $100
Ref-R	No	Rising from $75.24 in 2015 to $123.90 in 2050
Pol-50	Yes	Endogenous; oil resources consistent with those in the Ref-50 scenario
Pol-75	Yes	Endogenous; oil resources consistent with those in the Ref-75 scenario
Pol-100	Yes	Endogenous; oil resources consistent with those in the Ref-100 scenario
Pol-R	Yes	Endogenous; oil resources consistent with those in the Ref-R scenario

Note: * The carbon price rises from $25/t$CO_2$ in 2015 to $99/t$CO_2$ in 2050.

3. Scenarios

We consider the period 2015 to 2050 and specify eight scenarios that differ with respect to policies that are included and oil (and gas) prices. So that our results are comparable to the detailed analysis of bioenergy outcomes by Winchester and Reilly (2015), we consider the period 2015 to 2050 under the reference (*Ref*) and policy (*Pol*) cases simulated by these authors. The reference case assumes that each region develops according to 'business as usual' assumptions about economic, population and productivity growth and that there are renewable fuel mandates in the EU and the US. Renewable fuel policies in the EU are represented by imposing minimum energy shares for renewable fuel in ground transport of 5.75% in 2015, 10% in 2020 and 13.5% in 2030 and beyond, and constraining fuel produced using food crop to 50% or less of these targets. In the US, the 2015 and 2020 volumetric targets for different biofuel categories set out in the Energy Independence and Security Act of 2009 are imposed in 2015 and 2020. As the Act does not specify mandates beyond 2022, the volumetric targets in 2022 are converted to mandates expressed as a proportion of each biofuel in total transportation fuel in that year and enforced from 2025 through to 2050.

In the policy case, in addition to assumptions under the reference case, a global price on all GHG emissions except those from land-use change is imposed from 2015 to 2050. The carbon price is $25 per metric ton of CO_2 equivalent (tCO_2e) in 2015 and rises by 4% per year to $99/t$CO_2$e in 2050. Winchester and Reilly (2015) chose this carbon price to represent a cap on cumulative global emissions between 2015 and 2050 with banking of emissions and international trading of emissions permits.[1] This carbon price is not intended to represent proposed or future policies but is chosen to isolate the interplay between fossil fuel prices, bioenergy and emissions. Specifically, the global carbon price allows us to investigate how bioenergy and other low-carbon energy sources compete with fossil fuels without biases due to policies directed at specific technologies and differences in policy scope across regions.

We also consider four alternative reference oil price pathways. In one price pathway, the price of oil is determined by demand for fuels in the economy interacting with supply, as outlined in the endogenous oil price case in Section 2.2. In this specification, *Ref-R*, the oil price rises through time from, in 2010 dollars per bbl, $75.24 in 2015 to $123.90 in 2050. These price paths are in line with recent estimates from other sources. For example, oil price projections, in 2010 dollars, from EIA (2016) are $96.68/bbl for 2030 and $125.31/bbl for 2040; and from Lee and Huh (2017) are $81.52/bbl in 2030 and $97.60/bbl in 2040.[2]

In the other three price pathways, we impose constant oil prices from 2015 to 2050 in the reference policy case. The exogenous oil prices examined, in 2010 dollars per bbl, are $50, $75 and $100. As outlined in the exogenous price specification in Section 2.2, these prices are set by, in each period, endogenously scaling fossil fuel resources in all regions to target a specified price. As oil and gas prices are positively correlated – see, for example, Brown and Yücel (2008) – we apply the same scalar applied to oil resources to natural gas resources in each exogenous oil price case. In each policy scenario, oil and gas resources in each period are held constant at the level in the corresponding reference scenario, and oil and gas prices are endogenously determined by supply and demand. The eight scenarios simulated in our analysis are summarized in Table 2.[3] In the *Ref-R* scenario, labor productivity in each region and in each period is determined endogenously to calibrate to exogenous GDP estimates. Estimated values for labor productivity parameters from this scenario are then used in all other scenarios. As such, differences in oil and gas reserves across oil price cases lead to differences in GDP among the reference (and policy) scenarios.

4. Results

We organize results in three sub-sections, first analyzing the impact of changes in oil prices across the four reference scenarios. We then evaluate how alternative oil prices influence the impacts of the carbon price on energy production, GHG emissions, land use and other variables of interest. The third sub-section investigates the sensitivity of our results to the cost of LC ethanol production.

4.1. The reference scenario under alternative oil prices

Table 3 reports global GDP, primary energy, land use and CO_2 equivalent (CO_2e) emissions in 2050, and additional results are reported in Figs. 3–5. Beginning with the macroeconomic impacts of alternative oil prices, there is a negative relationship between GDP and oil prices as lower oil prices are simulated by increasing the endowments of fossil fuel resources. So, for example, global GDP in 2050 is $165.2 trillion in the *Ref-100* scenario and increases to $168.2 trillion when resource endowments are increased to simulate a lower oil price in the *Ref-50* scenario. The 1.78% decrease in GDP in the *Ref-100* scenario relative to the *Ref-50* is similar to the 1.86% decrease in GDP due to a doubling of the oil price estimated by Timilsina (2015).

Turning to energy production, global primary energy increases from 384.1 EJ in 2015 to 723.0 EJ in 2050 in the *Ref-100* scenario, with 660 EJ split roughly evenly between coal, oil and gas in this year (Fig. 3). Under

[1] The carbon price is simulated as a tax on CO_2 emissions with, in keeping with our treatment of fiscal policies elsewhere, tax revenue passed to the representative household in each region in a lump-sum fashion. As such, we do not evaluate revenue recycling implications and the 'double dividend hypothesis'.

[2] Lee and Huh (2017) report oil price projections in nominal dollars. Our conversion of their estimates to 2010 dollars assumes a future inflation rate of 2% per year.

[3] Under these assumptions, simulating paired reference and policy scenarios (e.g., *Ref-R* and *Pol-R*) under the same policy drivers would result in identical results in the two cases. However, relative to the reference scenario, the carbon price in the policy scenarios decreases oil demand and leads to a lower (net of the carbon price) oil price.

Table 3
Summary of global results in 2050.

	Ref-50	Ref-75	Ref-100	Ref-R	Pol-50	Pol-75	Pol-100	Pol-R
GDP (trillion, 2015$)	168.2	166.7	165.2	164.4	162.6	161.2	159.7	159.1
Primary energy (EJ)	861.2	767.2	723.0	703.0	549.4	529.6	528.0	517.8
Coal	226.4	221.2	223.8	224.4	52.1	50.7	48.8	48.2
Oil	325.0	260.8	226.5	200.4	236.3	191.8	158.3	143.2
Gas	251.7	223.1	209.4	201.1	141.1	132.1	125.2	122.1
Nuclear	15.5	19.0	19.8	20.8	22.8	22.8	23.9	24.2
Hydro	13.5	15.3	16.4	17.2	23.5	23.7	23.6	23.8
Wind & solar	9.1	9.3	9.6	9.6	14.1	14.1	14.5	13.6
Biomass	20.0	18.4	17.3	29.5	59.4	94.5	133.7	142.7
Bioenergy land (Mha)	10.3	8.9	8.0	13.1	37.3	79.1	138.6	150.5
Food crop land (Mha)	1809	1797	1784	1774	1752	1712	1671	1653
Natural Forest land (Mha)	3985	3991	3995	3997	3800	3815	3822	3826
CO_2e emissions (MMt)	86,917	79,421	76,362	73,814	48,546	44,812	41,827	41,136

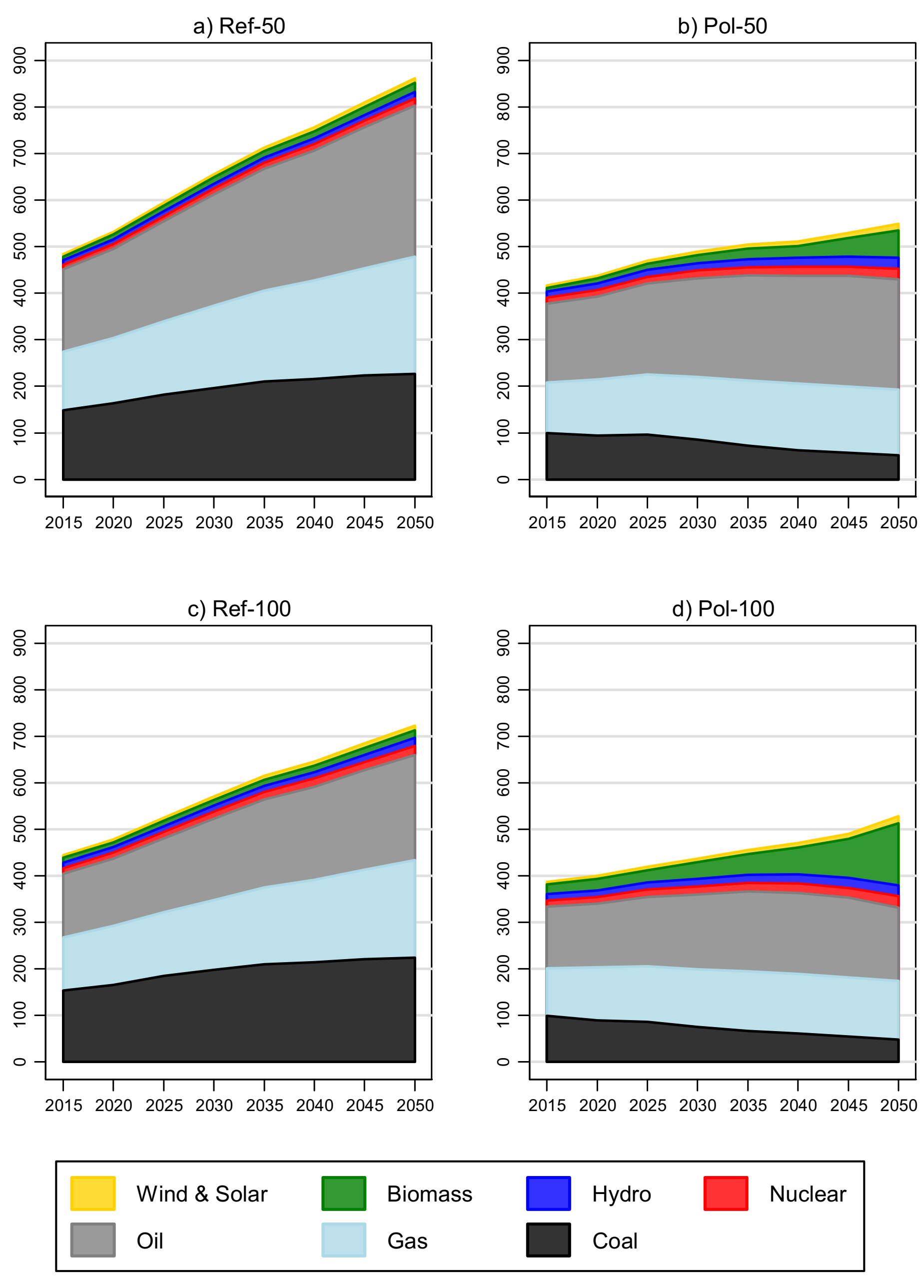

Fig. 3. Global Primary energy in the (a) *Ref-50*, (b) *Pol-50*, (c) *Ref-100*, and (d) *Pol-100* scenarios (EJ per year).

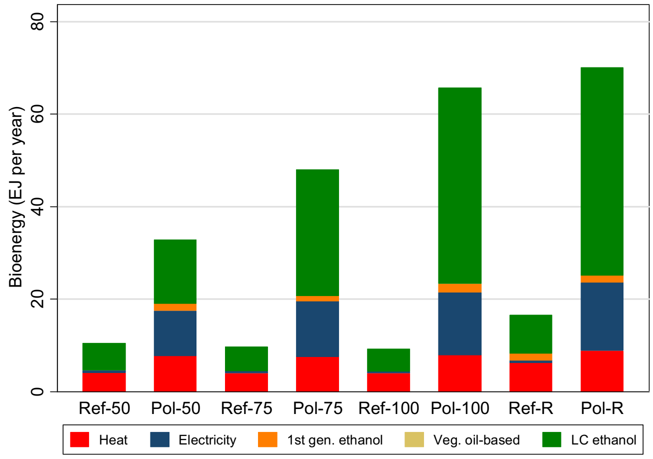

Fig. 4. Global bioenergy production.

the lower oil price in the *Ref-50* scenario, primary energy from oil and gas is, respectively, 43% and 20% higher than in the *Ref-100* simulation. The results also reveal a diminishing impact of oil price increases (in absolute terms) on energy use. For example, increasing the oil price from \$50 bbl to \$75/bbl decreases global oil use by 64.2 EJ, while an additional increase to \$100/bbl decreases it by another 34.3 EJ, and a further increase to \$124/bbl results in a marginal decrease of 26.1 EJ. However, the elasticity of oil use with respect to oil price is around 0.4 in all reference scenarios, indicating that the proportional impact of oil price changes is reasonably stable.[4]

Turning to bioenergy, there is 16% more primary energy from biomass in the *Ref-50* scenario than under the higher oil prices in the *Ref-100* scenario. This result is opposite to that expected under a pure price effect – where higher oil prices lead to more bioenergy production – and is driven by the renewable fuel mandates included in the reference scenario. Specifically, the fuel mandates in the EU and the US set minimum targets for renewable fuel as a proportion of total fuel use, so increased use of transportation fuels in scenarios with lower oil prices results in more biofuel production. However, as more bioenergy is produced in 2050 in the *Ref-R* scenario (which has an oil price of \$124/bbl) than other reference scenarios, there appears to be a non-monotonic relationship between the oil price and bioenergy production, indicating that there is a threshold oil price above which the pure price effect dominates the impact of the renewable fuel mandates.

In all reference scenarios, driven by the renewable fuel mandates and falling costs for this fuel, LC ethanol is the largest contributor to final bioenergy (Fig. 4). Other forms of bioenergy in 2050 include bioheat and electricity produced as a coproduct with LC ethanol. First generation biofuels, mainly sugarcane ethanol in Brazil and corn ethanol in the US, are a significant contributor to bioenergy in 2015, but they are replaced by LC ethanol over time as costs for this technology decline.

The small changes in bioenergy production across the reference scenarios have a small impact on land-use outcomes, and changes in land allocations are driven by changes in GDP, rather than bioenergy production. Specifically, lower oil prices lead to more land being used for food crops and less land allocated to natural forests, as higher incomes in scenarios with lower oil prices increase the demand for food. For example, at the global level in 2050, 1809 Mha and 1784 Mha are used for food crops in, respectively, the *Ref-50* and *Ref-100* scenarios, and the corresponding numbers for land allocated to naturals forests are 3985 Mha and 3995 Mha.

Global CO_2e emissions from all sources (including land-use change) in the reference scenarios are negatively correlated with the oil price and in 2050 range from 73,814 million metric tons (mmt) in the *Ref-R* scenario to 86,917 mmt in the *Ref-50* scenario (Table 3). Focusing on the contribution of fossil fuels, CO_2 emissions from these fuels range from 49,093 mmt in the *Ref-R* scenario to 60,405 mmt in the *Ref-50* scenario (Fig. 5a). Mirroring changes in oil use, each reduction in the oil price leads to progressively smaller reductions in emissions.

4.2. The impact of a global carbon price under alternative oil prices

The global carbon price simulated in our policy case decreases global GDP in 2050 by around 3.3% in each policy scenario relative to the relevant reference case. For example, GDP decreases from \$165.2 trillion in the *Ref-100* scenario to \$159.7 in the *Pol-100* scenario. The GDP results also indicate that, as in the reference scenarios, global GDP is higher when oil prices are lower due to increases in the endowment of fuel resources.

In each policy scenario, the carbon price decreases primary energy use relative to that in each reference scenario, with larger decreases – in both proportional and absolute terms – in scenarios with lower oil prices than those with higher oil prices (Fig. 3). For example, the carbon price decreases global primary energy in 2050 from 703.0 EJ in the *Ref-100* scenario to 528.0 EJ in the *Pol-100* scenario, a decrease of 195.0 EJ (26.3%), while the corresponding decrease in the *Pol-50* scenario relative to the *Ref-50* simulation is 311.8 EJ (36.2%).

The carbon price also changes the composition of primary energy, with decreases in fossil energy and increases in energy from other sources. As the most CO_2-intensive fossil fuel, coal experiences the largest decrease in use, which is around 175 EJ (78.5%) at the global level in 2050 in all oil price cases. Oil and gas use decrease by larger amounts in low oil price cases than in high oil price simulations, but by around the same proportional amount (39.3% for gas and 28.5% for oil) in all oil price cases. For example, relative to the *Ref-100* scenario, oil use decreases by 57.2 EJ (28.5%) in the *Pol-100* simulation, and the corresponding decrease in the *Pol-50* scenario is 88.7 EJ (27.3%). These results indicate that differences in the oil price have smaller impacts on the level of oil consumption (in absolute terms) under a carbon price than in the reference case.

Turning to low-carbon energy sources, there are moderate increases in primary energy from nuclear, hydro, and wind and solar, and relatively large increases in energy from biomass. The major forms of bioenergy in 2050 in the policy cases include LC ethanol, bioelectricity – mostly from dedicated bioelectricity production, but also as coproduct with biofuels – and bioheat (Fig. 4). Total biofuel production is 46.6 EJ (45.0 EJ from LC ethanol and 1.6 EJ from first-generation biofuels) in the *Ref-R* scenario and 15.3 EJ (13.8 EJ from LC ethanol and 1.6 EJ from first-generation biofuels) in the *Pol-50* scenario.

The amount of LC ethanol induced by the carbon price is more sensitive to the oil price than other forms of bioenergy. For example, in 2050, LC ethanol increases by 6.2 EJ due to the carbon price when the reference price of oil is \$50 per bbl and by 35.6 EJ when the reference oil price is \$100 per bbl, while the corresponding numbers for an aggregate of all other forms are bioenergy are 14.5 EJ and 19.1 EJ. Biofuels are relatively sensitive to changes in the oil price because they substitute for refined oil, while other forms of low-carbon energy still have to compete with coal.

The decreases in primary energy and increases in low-carbon energy induced by the carbon price decrease total emissions in 2050 by around 44% relative to the reference cases in all oil price scenarios. The corresponding decreases in emissions from fossil fuels is around 55%, with proportional decreases in emissions from each fossil fuel matching the proportional changes in use discussed above (around 78.5% for coal,

[4] The response of oil demand to price changes in the EPPA model is determined by several factors, including the ability to substitute between fuels, the willingness of consumers to substitute oil-intensive products for other goods and services, and the costs of alternative fuels and technologies. The 'general equilibrium' oil price elasticity simulated in the model (~0.4) is similar to long-run oil price elasticities estimated elsewhere. For example, using a model of resource discoveries, Organization of the Petroleum Exporting Countries cartel behavior and world oil demand, Rehrl and Friedrich (2006) estimate a long-run price elasticity of 0.458.

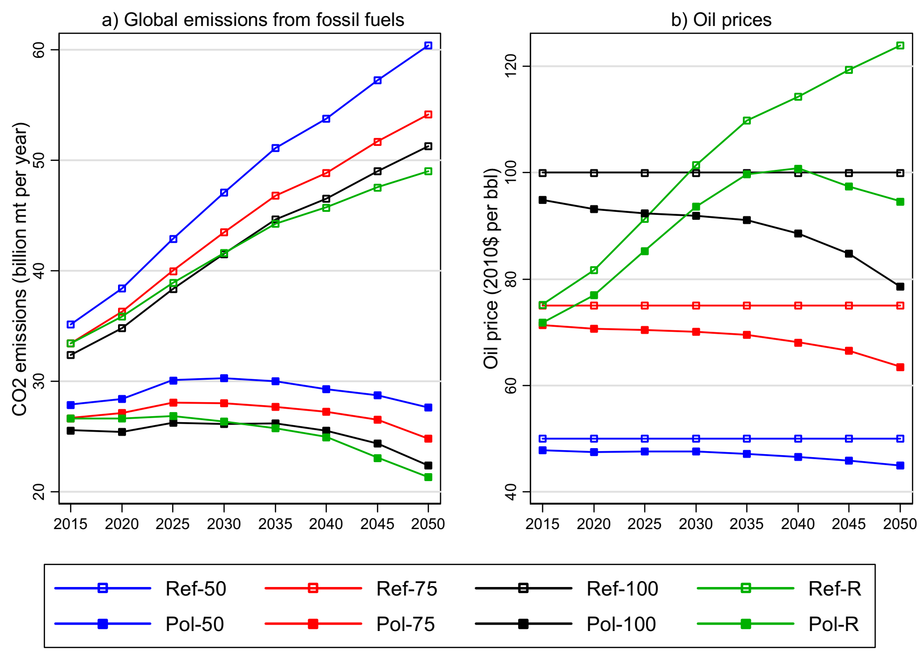

Fig. 5. (a) Global CO_2 emissions from fossil fuels (billion mt per year) and (b) Oil prices net of the carbon price (2010$ per bbl).

39.3% for gas, and 28.5% for oil in all oil price cases). As for oil consumption, the spread of emissions across oil price cases is smaller under the carbon price than in the reference scenario.

Given bioenergy production in the policy scenarios, changes in land used for bioenergy follow an expected pattern: more land is used for bioenergy crops in scenarios with higher oil prices (and more bioenergy production) than simulations with lower oil prices. Less land is used for food crops in scenarios with higher oil prices. This is partially due to increased bioenergy energy production but, as in the reference simulations, the main driver of changes in the demand for crop land is changes in incomes due to differences in endowments of fossil fuel resources. Relative to scenarios with lower oil prices, despite more land being used for bioenergy crops, decreased demand for land to grow food crops leads to more land used for natural forests in scenarios with higher oil prices. These results indicate that land-use changes are driven by income effects from changing resource endowments across oil price cases rather than changes in bioenergy production. This finding is consistent with other studies that conclude that bioenergy production has small impacts on land-use change (Winchester and Reilly, 2015).

As noted in Section 3, oil price is endogenous in all policy scenarios. The carbon price decreases the price of oil received by producers in all scenarios, with larger absolute decreases for higher oil prices cases than lower oil price cases (Fig. 5b). That is, as the carbon price increases and becomes a large component of the gross oil price, the producer price of oil converges across oil price cases.

4.3. Sensitivity analysis

As LC ethanol is the major form of bioenergy in all scenarios, we examine the sensitivity of the results to alternative costs for this fuel. We do this by changing conversion costs so that the cost of LC ethanol is multiplied by α. Our LC ethanol cost analysis focuses on the policy cases as bioenergy production is larger in these cases than in the reference scenarios. For the *Pol-75* and *Pol-100* scenarios, Table 4 reports global results in 2050 when $\alpha = ⅔$, $\alpha = 1$ (which replicates results for the two scenarios reported in Table 3), and $\alpha = 1⅓$. Comparing scenarios with the same LC ethanol costs reveals that increasing oil prices has similar qualitative impacts on modeling outcomes for the alternative LC ethanol costs considered.

The sensitivity analysis also allows us to compare the impact of alternative LC ethanol costs on the results at constant oil prices. In both scenarios, increasing the cost of LC ethanol reduces bioenergy production. As a result, less land is used for bioenergy crops and more land is allocated to food crops, and GHG emissions increase. An unexpected a priori result is that, in both policy cases, increasing LC ethanol costs results in a reduction in land allocated to natural forests. This result is driven by deforestation in Africa. Specifically, increasing LC ethanol costs leads to increased production of corn ethanol in the US and sugarcane ethanol in the Brazil at the expense of livestock production, which results in an increase in livestock production in Africa. As the land intensity of livestock production (ha per dollar of output) is much greater than that for LC ethanol production and Africa has low political barriers to deforestation, this results in deforestation in this region.

The results also reveal that an increase in the oil price has similar qualitative impacts as a decrease in LC ethanol costs. To quantify the impact of an increase in the oil price-LC ethanol cost ratio via the two channels, we calculate elasticities of bioenergy production with respect to this ratio using the *Pol-75* scenario when $\alpha = 1$ as a 'base' case. From this case, a 33.3% increase in the oil price-LC ethanol cost ratio due to an increase in the oil price (*Pol-100*, $\alpha = 1$) leads to a 41.5% increase in bioenergy production for a bioenergy production elasticity of 1.2. Alternatively, a 50% increase in the oil price-LC ethanol cost ratio due to a decrease in LC ethanol costs (*Pol-75*, $\alpha = ⅔$) results in an increase in bioenergy production of 97.2%, giving an elasticity of bioenergy

Table 4
Global results in 2050 for alternative LC ethanol costs.

	Pol-75			Pol-100		
	$\alpha = ⅔$	$\alpha = 1$	$\alpha = 1⅓$	$\alpha = ⅔$	$\alpha = 1$	$\alpha = 1⅓$
Biomass primary energy (EJ)	186.4	94.5	55.2	214.9	133.7	67.9
Biofuels	161.8	69.0	30.2	193.0	107.1	38.3
Non-biofuels	24.5	25.5	25.0	21.9	26.6	29.7
Bioenergy land (Mha)	219.3	79.1	44.2	261.9	138.6	63.1
Food crop land (Mha)	1641	1712	1734	1603	1671	1703
Natural Forest land (Mha)	3820	3815	3811	3833	3822	3820
CO_2e emissions (MMt)	40,721	44,812	47,278	38,268	41,827	45,398

production of 1.9. These calculations reveal that bioenergy production is more sensitive to changes in the oil price-LC ethanol cost ratio driven changes in LC ethanol costs than changes in this ratio due to oil price movements.

5. Conclusions

The price of petroleum-based fuels will be a key determinant of the penetration of biofuels in a low-carbon world. The level of bioenergy production will in turn influence outcomes for other forms of bioenergy, through competitions for feedstocks and land, and non-biomass energy due to energy market interactions. This paper quantified the impact of alternative oil price projections on energy production, GHG emissions, land-use change and economic outcomes out to 2050. The analysis employed the MIT EPPA model, a global applied general equilibrium model with a detailed representation of energy production. This model was used to simulate a 'reference' policy simulation, and a policy case that imposed a global carbon price that was \$25/tCO_2 in 2015 and rose to \$99/tCO_2 by 2050 under four alternative reference oil price projections. In three price projections, reference oil prices were held constant at, respectively, \$50, \$75 and \$100 per bbl by endogenously solving for the quantity of oil resources in each period that resulted in the desired price. To account for positive correlation between oil and gas prices, the same scale applied to oil resources was applied to gas resources in each period. In the other projections, the oil price in each period was determined by the interaction of extraction costs, demand, estimates of oil resources and extraction in previous periods. In this specification, the oil price rose from \$75/bbl in 2015 to \$124/bbl in 2050.

Under the global price, biofuels (mainly LC ethanol) were the major form of bioenergy in 2050, but there were large variations in the level of biofuel production depending on the oil price. When the 2050 reference oil price was \$123.90/bbl, global biofuel production was 46.6 EJ, but global biofuel production was only 15.3 EJ when the reference oil price was \$50/bbl.

Interestingly, as lower oil prices were simulated by increasing the endowments of both oil and gas resources, lower biofuel production when oil prices were lower did not result in an increase in production of other forms of bioenergy. This was because lower oil prices were simulated by increasing the endowments of oil and gas resources, which resulted in more energy from these sources.

CO_2 emissions from fossil fuels (and total GHG emissions) were negatively related to the oil price, and the carbon price decreased oil and gas use (and their associated CO_2 emissions) by more in low oil price scenarios than scenarios with higher oil prices. Consequently, the range in CO_2 emissions across oil price cases was narrower under the carbon price than in the reference scenarios.

Under the carbon price, more bioenergy production under higher oil prices resulted in more land being used to grow bioenergy crops, but changes in land use were dominated by income effects due to changes in resource endowments used to target alternative oil prices. Lower resource endowments (and incomes) in high oil price scenarios decreased the demand for land to grow food crops, which reinforced the land-use impacts of increased bioenergy production. Decreased demand for land to grow food crops also curtailed deforestation incentives so, despite more bioenergy production, more land was apportioned to natural forests in high oil price scenarios than in lower oil price scenarios.

Global models such as the EPPA model used in the study are operationalized using a large number of assumptions. Consequently, sensitivity analyses and examinations by multiple models are an important foundation for evaluating the robustness of results and developing an understanding of salient relationships between oil prices and bioenergy outcomes. This study contributed to this goal in several ways. First, the sensitivity analysis revealed that changes in the oil price have a larger impact on bioenergy outcomes than changes in LC ethanol costs that have the same impact on the oil price-LC ethanol cost ratio. This result has implications for studies that wish to capture uncertainty in future bioenergy costs relative to fossil fuel prices.

Second, some of our results reinforce findings from other studies. For example, Calvin et al.'s (2016) finding that lower CO_2 prices are needed to meet fixed emissions targets when there are less fossil fuel resources (higher oil prices) is consistent with our results showing that, under a fixed CO_2 price, GHG emissions are lower when fossil fuel prices are higher. However, our results also provide several new insights. Notably, in the policy settings considered by Calvin et al. (2016), decreasing oil resources (which resulted in higher oil prices) increases the use of bioenergy. In some cases considered in this paper, we observed the opposite relationship. Specifically, when biofuel use was driven by proportional mandates, increasing oil prices lead to a less fuel use and ultimately less biofuel use.

Third, we found that higher oil prices leads to an increase in areas allocated to natural forests. This result is at odds with an expectation that more bioenergy production will lead to deforestation, but is consistent with the decreases in resource endowments (which reduce food demand) used to generate higher oil prices in the model. Overall, our findings indicate it is important to consider the drivers of alternative oil prices, the economy-wide implications of changes in those drivers, and the interaction between oil prices and policies.

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