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Dynamic analysis of policy drivers for bioenergy commodity markets

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HIGHLIGHTS

- ► We model a United States bioenergy feedstock commodity market.
- ► Three buyers compete for biomass: biopower, biofuels, and foreign exports.
- ► The presented methodology improves on dynamic economic equilibrium theory.
- ► With current policy incentives and ignoring exports, biofuels dominates the market.
- ► Overseas biomass demand could dominate unless a CO_2-limiting policy is enacted.

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ABSTRACT

Biomass is increasingly being considered as a feedstock to provide a clean and renewable source of energy in the form of both liquid fuels and electric power. In the United States, the biofuels and biopower industries are regulated by different policies and have different drivers, which impact the maximum price the industries are willing to pay for biomass. This article describes a dynamic computer simulation model that analyzes future behavior of bioenergy feedstock markets given policy and technical options. The model simulates the long-term dynamics of these markets by treating advanced biomass feedstocks as a commodity and projecting the total demand of each industry, as well as the market price over time. The model is used for an analysis of the United States bioenergy feedstock market that projects supply, demand, and market price given three independent buyers: domestic biopower, domestic biofuels, and foreign exports. With base-case assumptions, the biofuels industry is able to dominate the market and meet the federal Renewable Fuel Standard (RFS) targets for advanced biofuels. Further analyses suggest that United States bioenergy studies should include estimates of export demand in their projections, and that GHG-limiting policy would partially shield both industries from export dominance.

1. Introduction

The use of biomass as a feedstock for energy production is one option to provide a clean, renewable, and domestic source of energy. Although biomass is a renewable resource, the amount that can be grown sustainably and accessed economically is limited (US Department of Energy (DOE), 2011a). In the United States (US), growth in the use of biomass feedstocks for energy production is increasingly being driven by governmental policies such as Renewable Fuels Standard (RFS) for biofuels production and Renewable Portfolio Standards (RPS) for biopower production (Sorda et al., 2010; US Department of Energy (DOE), 2010). However, the future size and strength of the bioenergy industry in the US is uncertain in the face of high values for biomass overseas that may drive up domestic prices for processed bioenergy feedstocks. Additionally, the potential for greenhouse gas (GHG)-limiting legislation creates uncertainty for investors in bioenergy and could disproportionately change the value of biomass for biopower compared to biofuel. The US Department of Energy (DOE) is investigating the utility of a commoditized uniform format for bioenergy feedstocks, which would expand access to many biomass industries and biomass resources, help minimize market volatility, and reduce risk to both biorefineries

Abbreviations: DOE, United States Department of Energy; EERE, DOE Office of Energy Efficiency and Renewable Energy; EISA, Energy Independence and Security Act of 2007; EPA, Environmental Protection Agency; EU, European Union; IEA, International Energy Agency; Gas, Petroleum-based gasoline; GHG, Greenhouse Gas; MYPP, OBP Multi-Year Program Plan; OBP, Office of Biomass Program within DOE, EERE; REC, Renewable Energy Certificate; RFS, Renewable Fuel Standard; RIN, Renewable Identification Number; RPS, Renewable Portfolio Standard; US, United States of America

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Nomenclature

Units of measure

$	US dollars
Bgal	Billion US gallon
gal	US gallon
GGE	Gallons of gasoline equivalent
Gl	Gigalitre, 1E9 litre
GW	Gigawatts of electric power
l	Litre, 0.001 m^3
MW h	Megawatt hour of electrical energy
Mton	Million US short ton
Mt	Million metric tonne
t	Metric tonne
ton	US short ton

and biomass producers (Hess et al., 2009; Searcy and Hess, 2010). While the uniform format removes some risk and limits to growth of bioenergy, it may enhance direct competition for bioenergy feedstocks among biopower, biofuels, and exporters. Therefore, as government and industry focus on the use of biomass as a commoditized feedstock for clean and renewable energy production, a need arises for techno-economic analysis regarding the effect of policies and strategies on the sustainability of multiple bioenergy industry sectors.

This study analyzes the emerging bioenergy industry by investigating patterns in the behavior of bioenergy feedstock markets given a range of technical and policy options. The article begins with a review of bioenergy technologies and policies that are creating a commodity market for bioenergy feedstocks. The core of the article presents the Bioenergy Market Model, which simulates the primary causes of growth in bioenergy feedstock markets and furthermore presents simulated scenarios that describe the effect of technologies and policies on three bioenergy industries: biopower, biofuels, and exports. This model also presents a graphical method of analyzing the dynamic allocation of commodities to multiple buyers given a revenue-maximizing supplier and allowing for supply or demand-limiting conditions. This is a new approach to dynamic market allocation that attempts to quantify instantaneous demand vs. price curves for potential buyers. Scenarios are presented that show a wide range of behaviors for the bioenergy feedstock market based on assumptions about the implementation of current bioenergy policy, the strength of export markets, the bioenergy technologies used, and the effects of greenhouse gas (GHG)-limiting legislation.

2. Technology description

2.1. Biofuels technology

To be economically viable, biofuels will need to be cost-competitive (after tax and subsidy) with conventional fossil fuel based transportation fuels such as gasoline. Although DOE's Office of Biomass Program is working with industry to develop, build, and operate integrated biorefineries at various scales (e.g., pilot, demonstration, and commercial), it is assumed in the mean time as these integrated biorefineries are designed and tested that conventional biorefineries can fill the gap. For the purpose of this study, we assume the economics of refinery production only hinge on liquid fuel cost targets that are based on competitiveness with conventional transportation fuels. From discussion, a nominal value of the cost target for biofuel at the output of the biorefinery is 0.79 $\$\,l^{-1}$ (3 $\$\,gal^{-1}$).

There are a variety of options for converting biomass into biofuels, generally divided into biochemical (biological-based) and thermochemical (heat-based) conversion processes. Although there are specific technologies within each of these general categories, biochemical conversion technologies, such as enzymatic hydrolysis, desire feedstocks with a high carbohydrate content and will be wet at the time of conversion (for example, Aden, 2008). Thermochemical conversion processes, such as gasification and pyrolysis, generally require a dry feedstock that is low in ash content and has a small, consistent particle size (for example, Phillips et al., 2007; Dutta et al., 2011). Because of these generalizations, herbaceous feedstocks that are naturally higher in ash and carbohydrates are generally allotted to biochemical conversion, while woody feedstocks with their lower ash content are directed to thermochemical conversion. Although yields for various conversion technologies vary greatly, we applied yields and costs from recent DOE design reports on biofuels production (Kabir Kazi et al., 2010; Dutta et al., 2011; Phillips et al., 2007) to simplify a model representing multiple disparate conversion processes down to conversion efficiency ($l\,t^{-1}$), which is the amount of biofuel produced per ton of biomass used, and conversion cost ($\$\,l^{-1}$), which is assumed to be a fixed cost over the annual timeframes considered herein.

2.2. Biopower technology

Biomass combustion to generate electricity has existed in the United States since the inception of the power grid. Historically, woody biomass, such as residues from timber harvesting, sawmilling, and pulp and paper, has been a feedstock to co-located, direct-fired boilers for electricity generation and/or heat. Agricultural residue, primarily from wheat and corn harvests, has also contributed to biopower production. These practices have grown the biopower industry into the third highest generator of renewable electricity in the nation next to hydropower and wind power, providing 12% of US renewable generation capacity in 2010 (Energy Information Administration (EIA), 2011a). Biopower is increasingly being targeted as an option to reduce GHG emissions from the electrical power industry. However, the existing paradigm of small, co-located plants is not economically scalable to reach large emission cuts. The biopower industry is therefore exploring the option of co-firing energy-dense biomass in existing coal plants at mixtures of up to 20% biomass to decrease emissions, meet renewable energy targets, and continue to support energy security (US Department of Energy (DOE), 2010). To be economically viable, this option must be cost-competitive with standard coal plants, and must also compete against other renewable technologies that may replace coal in the future.

This study considers co-firing biomass with coal as a domestic option for reducing GHG emissions from the electric power industry. Multiple technologies exist for modifying existing coal plants to co-fire biomass. Conventional woody feedstocks, such as debarked, chipped pine are readily available at many locations but may require significant modifications to the plant, including the potential for de-rating its output capacity. However, if the biomass is dried and energy density increased via a process such as torrefaction, a potentially low-cost heating method that reduces the biomass to near-zero moisture content and increases energy density, it behaves much more like coal and minimal modifications are necessary to existing coal plants assuming the co-feed remains below 20% biomass. Torrefied material also avoids the need to de-rate co-fed coal plants because its heat content is similar to that of coal (Tumuluru et al., 2010). Because coal plants are located throughout the US and have varying access to biomass, it is likely that a range of these technologies will be employed. For the purpose of this study, the performance of the biopower industry is concentrated into two variables. The first is the average biomass to electricity conversion efficiency (MW h t^{-1}) of all biopower plants, which is the amount of electricity produced by only the biomass portion per tonne of biomass used. This number will be higher if more plants choose to co-fire torrefied versus conventional feedstocks. The second technology variable is the added cost of retrofitting and operating a coal plant with biomass co-feed ($ MW h^{-1}). This cost is higher if more plants use conventional feedstocks.

2.3. Commoditized biomass

A major barrier to large-scale bioenergy development in the US is the continued availability of quality, economical biomass. The current practice for both the biopower and biofuels industry is to site plants near the biomass resource, such that the biorefinery is completely dependent on a single feedstock resource. This approach imposes many limitations on biorefinery planning, while increasing the risk of plant shut-downs due to supply chain disruptions, such as insufficient biomass yield (due to pests, drought, flood, etc.) and contract disputes with biomass suppliers (Hess et al., 2009). A biorefinery that does not have a sustainable feedstock supply is itself unsustainable. These plants are often designed around the properties of one or a few feedstocks and are entirely dependent on the local supply chain for availability and pricing. Because localized yields and characteristics of the biomass, such as moisture, ash, and carbohydrate content, can be highly variable, costs to produce large-scale fuel or power under this system will also be variable. Large-scale biopower and biofuels development will not be able to tolerate this wide-spread volatility.

A proposed solution to bioenergy feedstock quality and price volatility is to diminish the location dependency by creating a uniform feedstock supply chain that draws from a range of raw biomass types (Hess et al., 2009; Searcy and Hess, 2010). This system will create a bioenergy feedstock with standardized characteristics that may be easily transported, stored, and handled in existing high-capacity infrastructure. Although the benefits of a uniform-format system are extensive (Hess et al., 2009; Searcy and Hess, 2010), the most relevant to this study is the ability to buy and sell biomass on a commodity market. This advanced uniform feedstock design provides more market options for producers because farmers do not need to be contractually obligated to one buyer, and multiple industries, such as biopower and biofuels, will be able to bid for the same feedstock. This system creates bioenergy feedstocks that are tradable commodities, with all the classic economic benefits that commodities provide. For these reasons, this article concentrates on the behavior of a commoditized market for bioenergy feedstocks that are being accessed by multiple industries.

3. US bioenergy policy

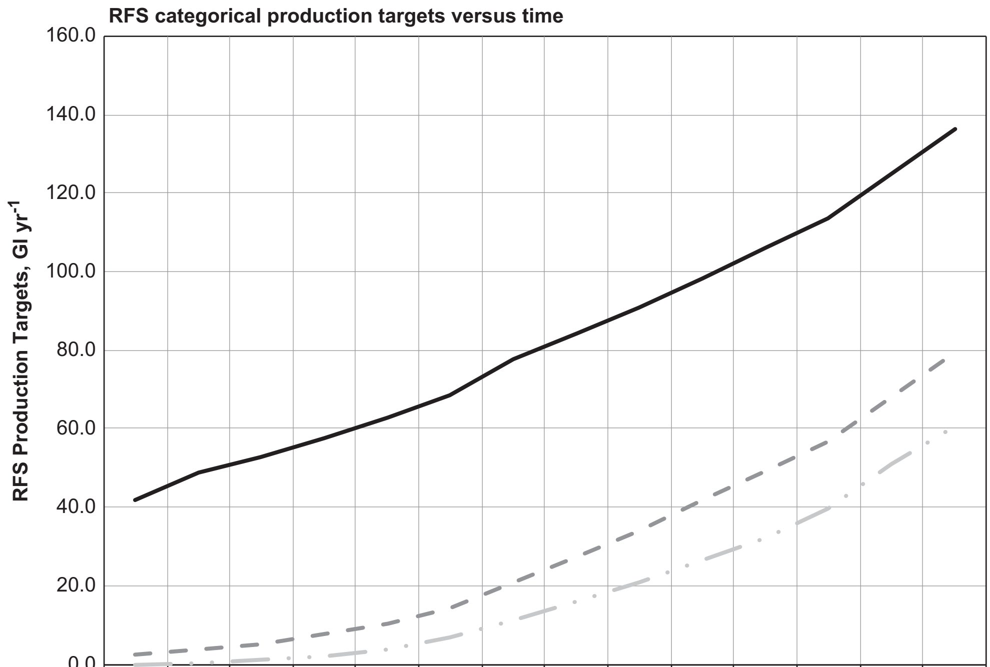
3.1. Biofuel policy

As outlined in the US Energy Independence and Security Act (EISA) of 2007, the DOE aims to increase renewable biofuel production from the current level of 42 Gl (10.5 Bgal) to 136 Gl (36 Bgal) by 2022. To reach this goal, the EISA expanded the National RFS Program, which sets targets for biofuel production that increase annually from 2012 through 2022. The RFS also gives the Environmental Protection Agency (EPA) statutory obligation to set a penalty which is assessed to producers who miss their annual production targets. The new RFS decomposes biofuel targets into categories to ensure that they are met in a sustainable and equitable manner. The definition of ethanol-specific categories along with their respective RFS volume targets are illustrated in Fig. 1. Targets for overall renewable biofuel follow a linearly increasing pattern, while targets for advanced and cellulosic biofuels follow an exponentially increasing pattern. It is assumed that conventional corn-based renewable biofuels will fill the gap between the total renewable biofuel requirement and the advanced/cellulosic components, with the overall fraction contributed by corn-based biofuel decreasing through time. This study concentrates on the subset of the biofuels industry that DOE terms *advanced* because these are the most likely to use commoditized bioenergy feedstocks and also the most likely to experience direct competition with other bioenergy industries. The types of biofuels eligible for consideration as advanced may include several conversion technologies:

- Ethanol derived from cellulose, or lignin
- Ethanol derived from sugar or starch (other than corn starch)
- Ethanol derived from waste material
- Biomass-based diesel
- Biogas
- Butanol or other alcohols produced through the conversion of organic matter from renewable biomass
- Other fuel derived from cellulosic biomass (EISA, 2007).

Renewable Identification Numbers (RINs) are the policy-driven mechanism for ensuring that prescribed targets under the RFS are met. A RIN is a 38-character code that is issued at the point of biofuel production or import, and reported to the EPA at that time. One RIN is attached to each gallon of biofuel produced, transferring ownership along with that biofuel until it is blended or refined into a motor vehicle fuel. At that point, the RIN may be used for RFS compliance, held for a maximum of 2 years for future compliance, or traded into a RIN market. Companies that sell motor vehicle fuels are obligated to submit to the EPA a quantity of RINs proportional to their total fuel production for RFS compliance, either through blending with RIN-producing fuels or by buying them from the RIN market. There are five separate RIN categories separated by technology: cellulosic biofuel, advanced non-cellulosic biofuel, standard biodiesel, cellulosic biodiesel, and other renewable fuel (US Environmental Protection Agency (EPA), 2010). All of these RINs, except for the "other renewable fuel" category, may be turned in to meet the advanced RFS volume obligation, as long as sub-mandates are met. Therefore, we concentrate on the average value of RINs that count towards the advanced biofuel targets.

The price of a RIN in some respects provides insight into the impact of RFS mandates on bioenergy feedstock markets. Essentially, high RIN prices reflect a strong impact of mandates on the market, while low RIN prices mean that market expansion may not be driven by mandates alone (McPhail et al., 2011). The RIN market practically ensures compliance with RFS targets because the RIN price theoretically bridges the gap between the transportation industry's willingness to pay for biofuel and the fuel industry's willingness to produce it. In the case that a company cannot produce RINs for its obligation, the EPA may allow that company's deficit to roll over until the following year or set a penalty price that would effectively cap RIN prices. Ultimately, the details of RIN policy will determine whether the market is effective. As Ford et al. (2007) showed for similar energy



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Cellulosic Biofuel	0.0	0.4	0.9	1.9	3.8	6.6	11.4	16.1	20.8	26.5	32.2	39.7	51.1	60.6
Advanced Biofuel	2.3	3.6	5.1	7.6	10.4	14.2	20.8	27.4	34.1	41.6	49.2	56.8	68.1	79.5
Total Renewable Biofuel	42.0	49.0	52.8	57.5	62.6	68.7	77.6	84.2	90.8	98.4	106.0	113.6	124.9	136.3

Renewable Biofuel: "fuel produced from renewable biomass… used to replace or reduce the quantity of fossil fuel present in a transportation fuel."

Advanced Biofuel: "renewable fuel other than ethanol derived from corn starch for which lifecycle GHG emissions are at least 50% less than the gasoline or diesel fuel it replaces."

Cellulosic Biofuel: "renewable fuel derived from any cellulose, hemicellulose, or lignin, each of which must originate from renewable biomass." (EPA, 2010)

Fig. 1. United States RFS targets for biofuel production. This study concentrates on the advanced category.

certificate markets, uncertainty, speculation, and construction delays often cause these types of markets to hit their price cap early and oscillate around a fundamental price over time, even without perturbations in supply or demand. In this article, the RIN price is assumed to work stably as designed to ensure RFS compliance. An effective cap on RIN values is included that lowers uncertainty and limits industry burden. We track the fundamental RIN value to biofuel producers, and do not address the speculative components and market inefficiencies that may also increase RIN prices.

3.2. Biopower policy

The DOE biopower workshop held in December 2010 cited the lack of a federal RPS and the lack of comprehensive carbon legislation as two of the largest policy-related hindrances to biopower development in the US (US Department of Energy (DOE), 2010). Because no federal RPS presently exists, policy-induced incentive for biopower development is currently driven by state RPS legislation. Currently, there are 24 states and the District of Columbia with RPS policies in place, accounting for over half of U.S. electricity sales. Five states – North Dakota, South Dakota, Utah, Virginia, and Vermont – have set voluntary goals instead of RPS that have binding targets. RPS targets and timeframes differ in each state. Their cumulative contribution to national renewable electricity targets as a percentage of the national electrical demand is illustrated in Fig. 2 (US Department of Energy (DOE), 2012a; Energy Information Administration (EIA), 2011b). If the distribution of demand among these states remains relatively proportional through time (e.g., a state that represents 4% of national demand now will represent 4% in 2020), the current sum of mandatory RPS calls for approximately 11% of national electricity to be generated by renewable sources in 2030, which equates to 56.5 GW of average renewable generation if national electricity demand grows at a rate of 1% per year. Because it is uncommon for state RPS policy to include significant technology-specific targets similar to the RFS, biopower must compete against other renewable electricity technologies to satisfy these targets.

In response to state RPS requirements, multiple markets have arisen for the trade of Renewable Energy Certificates (RECs). Similar to RINs, RECs are awarded and priced for every 1 MW h generated by a renewable energy source. For compliance markets (e.g., markets in which the RPS targets are mandatory) the REC must be generated within the same geographical boundary as the market. Voluntary markets have also arisen, in which RECs may be generated anywhere in the nation. Currently, compliance REC prices vary between 2 and 40 $ MW h^{-1} depending on the market (US Department of Energy (DOE), 2012b). This high discrepancy is a result of a wide range of policy details, as well as the highly variable cost to develop renewable energy in different geographies. With similar assumptions to this article, Ford et al. (2007) calculated that a national REC price required to induce a switch from coal to a mix of natural gas and renewable sources is 15 $ MW h^{-1}. This is assumed to be the incentive needed to spur investment in the development of new projects that are relatively

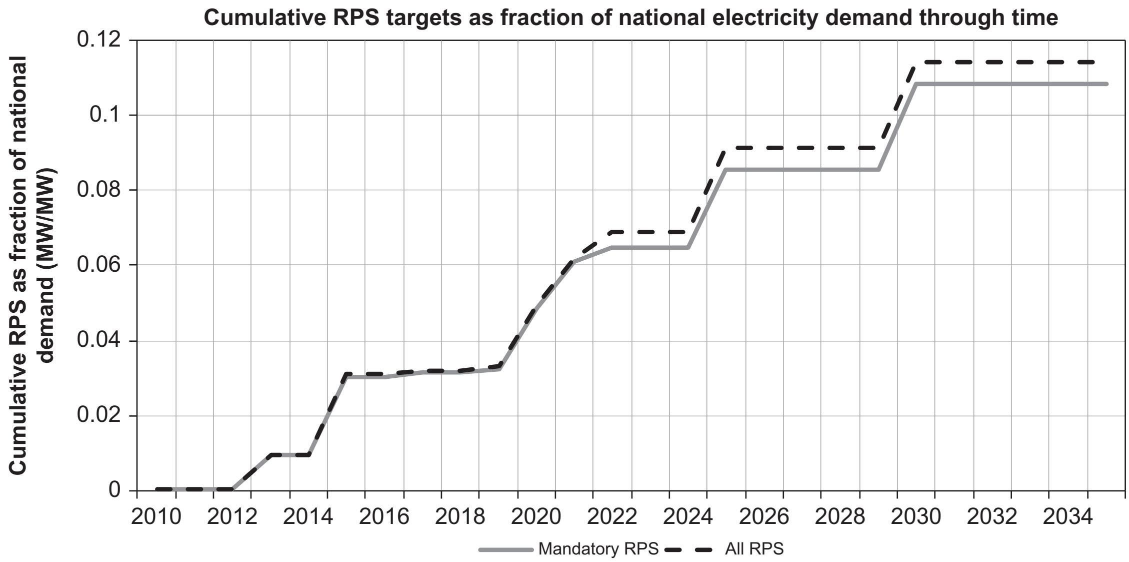


Fig. 2. Aggregated state RPS targets as a fraction of national electricity demand.

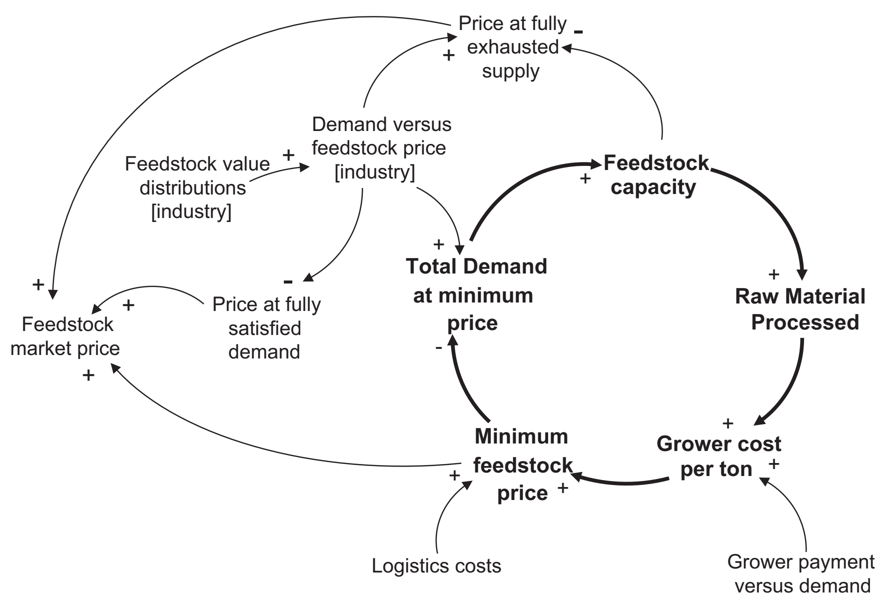


Fig. 3. Causal loop diagram of a bioenergy feedstock market, with the dampening feedback loop in bold.

capital-intensive as compared to the biomass co-feed technology that is assumed here. This suggests that a 15 $ MW h^{-1} REC price is a fundamental mode that the market may settle on to induce investment in renewable energy projects such as wind and solar. If biopower is not competitive at this fundamental REC price, it is unlikely to develop at a large scale since other technologies will meet the RPS targets. Therefore, the fundamental 15 $ MW h^{-1} REC price is assumed to be steady and unaffected by biopower development in this analysis, and biopower is assumed to be able to satisfy up to 50% of RPS-induced demand without significantly affecting the fundamental REC price.

4. Model development

The Bioenergy Market Model simulates policy-relevant inter-annual dynamics of a biomass commodity market for bioenergy development. Focusing on biomass feedstocks as a commodity, it projects the supply, demand, and market price for the aggregate advanced bioenergy feedstocks over time. The model currently focuses on three industry sectors that compete for biomass: biofuels, biopower, and foreign exports. By dynamically expanding the supply capacity of the bioenergy feedstock based on perceived demand, the simulated commodity seller sets its price and allocates its product among the industries according to their demand versus price relationships. The Bioenergy Market Model is used to test both policy and technology scenarios that drive competition between the three industry sectors, with a concentration on leverage points that can create desirable outcomes.

4.1. Theory

The essential source of dynamic behavior in the Bioenergy Market Model is the balancing feedback loop that tends to slow the growth in the bioenergy industry over time. Referencing Fig. 3, this feedback loop illustrates that the group of suppliers target feedstock supply capacity to meet the perceived demand at the suppliers' absolute minimum selling price, which is primarily dependent on supply chain costs. The instantaneously perceived demand reflects a seller that is targeting marginal demand to maximize profit, in other words targeting a market where marginal utility of trading additional biomass is just above zero. Because demand is highly price dependent, and the minimum feedstock price is a function of supply capacity via variable grower payments, the realized demand is dynamically dependent on supply capacity. Assumptions about how each of these variables responds causally to its contributing factors determine the strength of the loop, and the resistance to industry growth. The primary assumption is that the structure of this loop reflects the behavior of a bioenergy feedstock market.

The causal loop diagram in Fig. 3 was developed with insights from economic equilibrium theory, which states that commodity markets tend to seek a price at which supply meets demand, and this phenomenon balances perturbations of supply or demand that clears the market over time (Varian, 1992). In the dynamic case, supply and demand need not necessarily be equal at any one point in time, but the commodity price is targeting this condition (Mantel, 1974; Debreu, 1974). In the Bioenergy Market Model, the bioenergy industries are consumers, each with a dynamically calculated demand versus price relationship. The suppliers are biomass processors that follow bioenergy feedstock technology roadmaps to develop a biomass commodity. To maximize profit, the suppliers attempt to match total feedstock capacity to the total perceived demand at their minimum price for the bioenergy feedstock. The minimum price is that at which the suppliers' marginal profit shrinks to zero, which is assumed to be equal to the suppliers' cost of producing the bioenergy feedstock in this analysis.

To determine the partitioning of the bioenergy feedstock among industry sectors, the model draws from multinomial logit theory of discrete choice. Economists use the multinomial logit function when the utility of multiple discrete choices depends on a single set of variables, and alternative choices are not correlated with each other (Menard, 2002). In the case of bioenergy feedstocks, the choice is how much biomass a particular industry will buy at a market price given alternatives for that industry's goals. The multinomial logit function returns the probability of choosing each alternative given its utility versus those of the remaining alternatives. As the number of decisions becomes very large, this probability is equal to the proportion of total decisions made in the alternative's favor. In the case of economic commodity partitioning, each alternative is assumed to have a distribution of marginal demand versus commodity price that may overlap with those of other alternatives. The Bioenergy Market Model extends this assumption by developing normally distributed marginal demand curves, as is shown in Fig. 4. Each distribution's mean is the average economic value of the bioenergy feedstock to that industry. The standard deviation of each distribution represents the assumption that these industries contain multiple non-uniform buyers, similar to the assumptions of multinomial logit theory. The supplier's minimum price is depicted as a vertical line in Fig. 4. The multinomial logit function would return the proportional area of each distribution that is shaded by this vertical line. In the example of Fig. 4, the biofuels industry is satisfying around 65% of its instantaneous fuel demand potential using biomass, presumably meeting the remainder with an alternative technology or simply producing fuel at less than maximum capacity. Biopower and exports have cheaper alternatives to meet their goals, and therefore do not play in the bioenergy feedstock market in this example. Because the multinomial logit does not reflect situations that are dynamically supply or demand limited, we developed an alternative solution to calculate the instantaneous market price.

At every point in time, the Bioenergy Market Model simulates the market described in Fig. 4 by assuming that the supplier is attempting to maximize profit, setting the bioenergy feedstock price accordingly. To maximize profit, the supplier takes the highest bids from consumers in Fig. 4, approaching the incremental demand curves from right to left and satisfying this demand until one of three conditions is met: (1) it reaches the minimum price at which marginal profit approaches zero; (2) it exhausts supply; or (3) it meets all quantity demanded. In this way, industries with a higher value for the commodity will submit higher bids, and will receive a higher proportion of the commodity partition. This high-to-low value integration is presented in Fig. 5. Cumulative distributions on the left are stacked to represent the total instantaneous demand at a particular feedstock price. The supplier is defined by a minimum price (vertical line) and a maximum instantaneous supply (horizontal line). The market price is that at which the demand and supplier curves intersect, or the price at which all quantity demanded is satisfied, whichever is highest. In this way, assumptions of a competitive commodity market are satisfied and a value-based commodity partitioning is accomplished, including dynamically supply or demand limited conditions. While similar to classical economic supply and demand theory, the curves represent the capacity of the market at any one point in time, and do not include demand or supply that would be added in the future.

4.2. Implementation

The causal loop diagram of Fig. 4, as well as the price setting and commodity partitioning algorithm described previously, were implemented using the System Dynamics methodology described by Sterman (2000) and Ford (2010). System Dynamics is useful for computer simulation of complex interactions between disparate variables with explicit implementation of feedback. Using a visual programming language consisting of accumulators (stocks), flows, and delay-inclusive feedback, the modeler is able to simulate causal interactions through time. The Bioenergy Market Model simulates

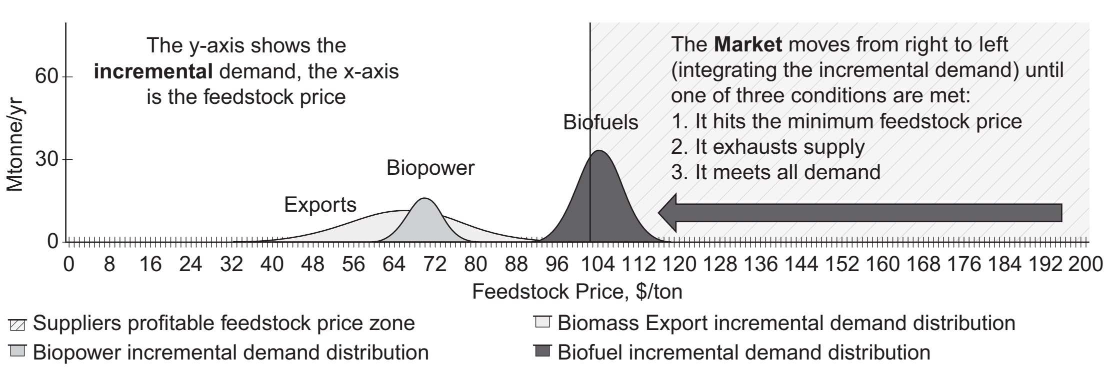


Fig. 4. Graphical representation of dynamic commodity pricing with three consumers represented by marginal demand curves.

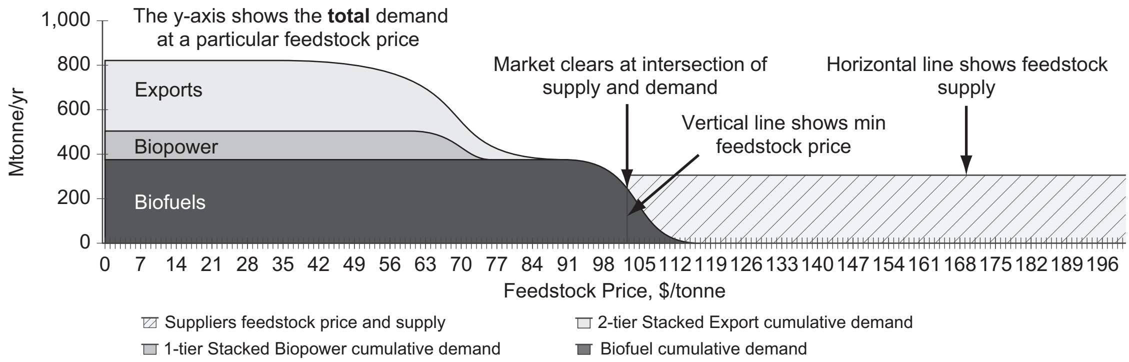


Fig. 5. Graphical representation of dynamic supply and demand curves. These differ from classical economic supply and demand curves in that they represent the instantaneous capacities of suppliers and consumers.

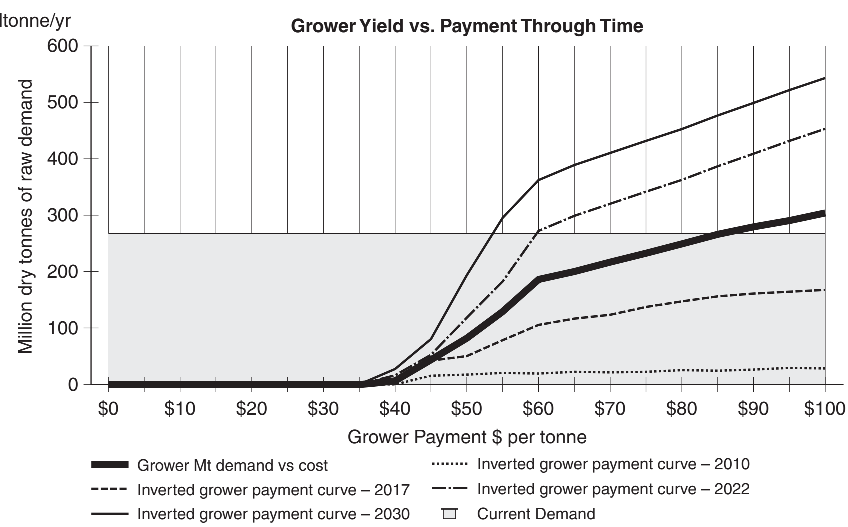


Fig. 6. Discrete curves of raw biomass availability versus grower payment for multiple years are shown with lighter weight, while the heavier curve represents the interpolated grower payment curve during year 2020 of the simulation. The intersection with the grey demand line is the current grower payment, approximately 86 $ t^{-1} in this example.

the growth of the bioenergy feedstock market over multiple years with sub-annual resolution. The version described herein simulates market behavior from 2010 to 2030 and runs quickly for instant user feedback. Assumptions can be edited by moving slider bars or clicking graphs. Output charts and tables are continuously updated as the model runs. The model may run an entire simulation or can be paused mid-run to allow the user to change settings.

To develop the normal distributions of marginal demand by industry sector in Fig. 5, the model uses three parameters for each industry: (1) the mean economic value of the bioenergy feedstock; (2) the standard deviation of that value; and (3) the maximum instantaneous demand. For the export sector, the driving factors for these parameters are nebulous and are left as a manual input from the user. For the biofuels and biopower industries, the standard deviation is manually entered, but the mean value and the maximum demand are calculated based on technical and policy drivers. The biofuels industry builds capacity in proportion to the difference between the marginal cost of producing biofuels and their cost targets. This dynamic capacity calculation determines the biofuels industry's maximum instantaneous demand. The mean economic value of the feedstock to the biofuels industry is calculated using Eq. 1:

$$\overline{V}_f = (C + I_{RFS} + I(P_{\mathrm{GHG}})_{Fuels} - P) \times \eta_f, \tag{1}$$

where: V_f is the value of feedstock to the biofuels industry [$ t^{-1}]; C the cost target of the biofuels industry [$ l^{-1}]; I_{RFS} the total incentive from *RFS* policies [$ l^{-1}]; $I(P_{\mathrm{GHG}})_{Fuels}$ the biofuel incentive as function of GHG policy [$ l^{-1}]; P the biofuels levelized cost, excepting fuel costs [$ l^{-1}]; η_f the efficiency of biofuel conversion process [l t^{-1}].

Eq. (1) is based on the assumption that the biofuels sector is a collection of cost-driven companies that will attempt to buy RINs if they cannot meet externally-driven cost targets.

Similar to biofuels, the biopower industry is driven by equations for demand and mean economic feedstock value. The biopower industry is assumed to be dominated by existing coal-fired facilities that may co-feed biomass to acquire RECs and/or GHG credits. Because most RPS targets do not mandate biopower specifically, the maximum demand for bioenergy feedstocks is assumed to be proportional to but less than the nationally cumulative RPS target. The fraction of total renewable electricity requirements that could potentially be filled by biopower is set by the user. Eq. (2) calculates the mean economic value of the bioenergy feedstock to the biopower industry:

$$\overline{V}_p = (Z + I_{RPS} + I(P_{\mathrm{GHG}})_{Power} - \Delta LC) \times \eta_p, \tag{2}$$

where: V_p is the value of feedstock to the biopower industry [$ t^{-1}]; Z the price of electricity from coal [$ MW h^{-1}]; I_{RPS} the total incentive from *RPS* policies [$ MW h^{-1}]; $I(P_{\mathrm{GHG}})_{Power}$ the biopower incentive as function of GHG policy [$ MW h^{-1}]; ΔLC the additional levelized cost of co-firing biomass [$ MW h^{-1}]; η_p the efficiency of biopower conversion process [MW h t^{-1}].

This equation states that coal plants will revert to using a pure coal feed unless the overall cost, including all incentives, of generating power with biomass is cheaper. The incentive from RPS policies is essentially the value of a REC, and the effect of biopower practices on REC prices is assumed to be minimal.

In concurrence with calculating the marginal demand versus price distributions, the supplier's capacity, and the supplier's minimum price, the model runs the price setting and feedstock-partitioning algorithm described in Section 4.1. By integrating Fig. 4 from high to low feedstock prices, the model creates Fig. 5, providing the cumulative demand versus price relationship. The maximum of the price at fully satisfied demand, the supplier's minimum price, and the price to clear full supply is the instantaneous market price for the bioenergy feedstock. This price is used in a lookup fashion using the cumulative demand versus price relationship to determine the amount of feedstock material that is allocated to each sector. By using this model, realistic projections of bioenergy feedstock market behavior can be examined given multiple assumptions about policy and technology.

In the Bioenergy Market Model, the ability of the supplier to acquire and process biomass into a bioenergy feedstock is represented with a stock that changes in response to dynamically changing demand at the seller's minimum price. This stock represents the total supply of the bioenergy feedstock supplier and is represented by a horizontal line in Fig. 5. The supplier's minimum price, which is the vertical line in Fig. 5, is the sum of logistics costs and payments to the biomass grower. Logistics are simulated as a constant cost per ton of processed biomass, decreasing at a constant improvement rate through time. This simulates the asymptotic decline in supply chain costs often observed with technology learning curves. Grower payments are simulated as a function of demand for multiple years as illustrated in Fig. 6. The sloping curves in this figure represent the total amount of biomass available at a particular grower payment for multiple discrete years. At the beginning of the simulation, the marginal cost of acquiring raw biomass is high. This marginal cost decreases through time as agricultural and silvicultural byproducts become more readily available, and as more energy-specific growth takes place. The model simulates this behavior by interpolating discrete grower payment curves through time, moving from the bottom curve in Fig. 6 to the top curve over the course of the simulation. The x-axis point where the actual demand intersects the interpolated grower payment curve is the simulated price of raw biomass.

5. Simulation scenarios

In response to communication with bioenergy subject matter experts, four scenarios were developed that reflect important policy and technical issues facing the industry (Haq, Z., personal communication, March 2012). The first scenario is a base case that simulates a best estimate of bioenergy feedstock market behavior under current technology and policy projections. The second scenario calculates the additional incentive that would be needed for biopower to meet 50% of RPS targets under the base case assumptions. The third scenario tests assumptions about the impact of a high-demand export market. The fourth scenario tests the growth of this market assuming a price for GHG emissions.

Table 1
Technology and policy parameters, (——) indicates no change from base case.

Model section	Parameter	Unit	Scenarios		
			Base case	GHG cap	Export competition
Policy and demographics	Fraction of RPS open to biopower		0.5	—————	—————
	Fundamental REC price[a]	$ MW h^{-1}	15	—————	—————
	Electricity load growth fraction	% yr^{-1}	1	—————	—————
	RIN lower collar price	$ l^{-1}	0	—————	—————
	RIN upper collar price	$ l^{-1}	0.13	—————	—————
	RIN market response time	yr	1	—————	—————
	Effective CO_2 emission price[b]	$ t^{-1}	0	40	—————
Logistics and preprocessing	Logistics farmgate to facility cost[c]	$ t^{-1}	49.4	—————	—————
	Logistics improvement rate	%/yr	1	—————	—————
	Supplier expansion time	yr	1	—————	—————
Biopower	Biopower conversion efficiency[d,e]	MW h t^{-1}	2	—————	—————
	Coal electric conversion efficiency[f]	MW h t^{-1}	2.2	—————	—————
	Biopower stddev feedstock value	$ t^{-1}	3.3	—————	—————
	Biopower levelized conversion cost[d,e]	$ MW h^{-1}	8	—————	—————
	Coal levelized conversion cost[f]	$ MW h^{-1}	7.5	—————	—————
	Price of coal feedstock[g]	$ MW h^{-1}	20.4	—————	—————
Biofuels	Biofuel conversion efficiency[h]	l t^{-1}	333	—————	—————
	Biofuel stddev feedstock value	$ t^{-1}	3.3	—————	—————
	Biofuel levelized production cost[h]	$ l^{-1}	0.49	—————	—————
	Biofuel refinery construction time	yr	0.5	—————	—————
	Biofuel gasoline equivalent[i]	l l^{-1}	1.4	—————	—————
Exports	Mean value of feedstock for exports	$ t^{-1}	66	—————	154
	Biomass Export stddev feedstock value	$ t^{-1}	11	—————	—————

[a] Ford et al. (2007).
[b] Energy Information Administration (EIA) (2009).
[c] Hess et al. (2009).
[d] Center for Climate and Energy Solutions (C2ES) (2009).
[e] US Department of Energy (DOE) (2010).
[f] International Energy Agency (IEA) (2010).
[g] Energy Information Administration (EIA) (2012).
[h] US Department of Energy (DOE) (2011b).
[i] Wu et al. (2006).

5.1. Current policy trajectories without export competition

The base case for the Bioenergy Market Model simulates behavior of the bioenergy market in the United States if current policies that drive its development stay in place for twenty years and the US does not become a major feedstock exporter. Principal to these assumptions are the RFS and RPS targets and their associated incentives. This scenario assumes that the commoditized bioenergy feedstock represents all operations that the RFS legislation terms *advanced*, meaning renewable, non-corn-based feedstocks that constitute a net 50% GHG emission savings compared to the fuel it replaces. The advanced RFS targets depicted in Fig. 1 drive RIN prices in this scenario and the biofuels industry targets a total value of 0.79 $ l^{-1} (3 $ gal^{-1}) for their produced fuel. The value of advanced RINs starts at 0.026 $ l^{-1} (0.10 $ gal^{-1}) and dynamically changes to target compliance with the RFS up to an effective cap set by the EPA which is assumed to be 0.13 $ l^{-1} (0.50 $ gal^{-1}). Advanced biofuel is produced from a variety of feedstocks, including torrefied and non-torrefied woody and herbaceous materials using a range of technologies that yield 333 l t^{-1} (80 gal ton^{-1}) on average at a total levelized production cost of 0.49 $ l^{-1} (1.85 $ gal^{-1}) (US Department of Energy (DOE), 2011b).

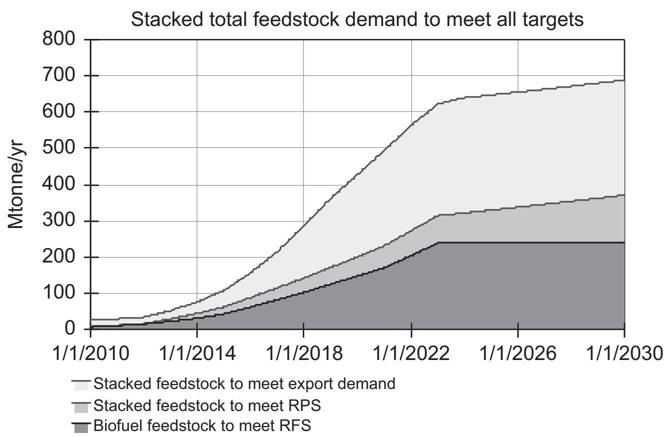


Fig. 7. Stacked plot of biomass demand for three major consumers.

For biopower, RPS requirements remain as they stand in spring 2012 and only mandatory RPS states enact binding REC markets. Biopower is assumed to be able to capture 50% of the new renewable energy demand without significantly affecting the fundamental REC value. Volatility in REC markets is controlled to the point that discrete jumps in RPS targets as illustrated in Fig. 2 may be ignored and a linearly increasing RPS-induced demand is used. The REC price is proportional to the slope of the RPS, peaking just above 15 $ MW h^{-1} and using an initial price floor of 5 $ MW h^{-1} as suggested by Ford et al. (2007). The biopower industry targets a total generation cost on par with the average coal plant, approximately 27.9 $ MW h^{-1} in this scenario (Energy Information Administration (EIA), 2012). Biopower is assumed to co-fire existing coal plants with a 20% mixture of torrefied and non-torrefied materials that produce a national average production efficiency of 2.0 MW h t^{-1} at an increased levelized production cost of 0.50 $ MW h^{-1}, as compared to pure coal firing (Center for Climate and Energy Solutions (C2ES), 2009; US Department of Energy (DOE), 2010).

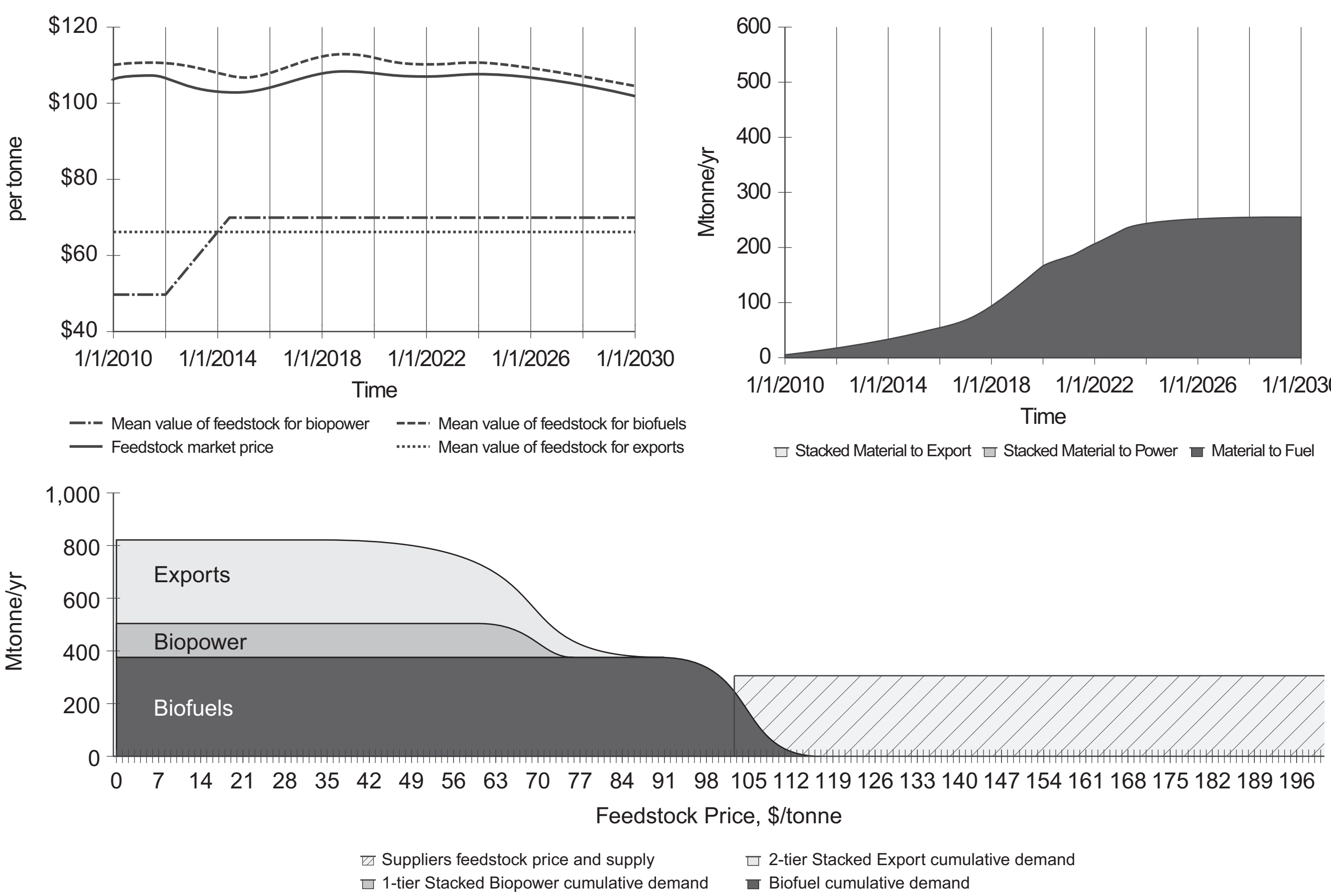


Fig. 8. In the base case, market prices are stable and biofuels dominates demand.

The export sector is assumed to be a non-player in this scenario, so it offers on average $66\ \$\ t^{-1}$ for the processed feedstock at US ports. The relationship of grower payment to demand through time is matched to the baseline assumptions in the DOE Billion Ton Update (US Department of Energy (DOE), 2011a). Logistics of feedstock processing from fieldside to market are assumed to start at $49.4\ \$\ t^{-1}$ and improve at a rate of $1\%\ yr^{-1}$ throughout the simulation period based on results from the Idaho National Laboratory's Biomass Logistics Model assuming a balanced advanced woody and herbaceous supply chain (Hess et al., 2009). The remaining technology-related parameters are illustrated in Table 1. With these assumptions, Fig. 7 illustrates the total bioenergy feedstock that would be necessary to meet all RFS targets for advanced biofuels, 50% of mandatory RPS targets using biopower, and an assumed growth in export demand. Biofuels and biopower alone require over $370\ Mt\ yr^{-1}$ ($410\ Mton\ yr^{-1}$) of processed biomass to meet targets by 2030, while total potential demand including exports grows to $690\ Mt\ yr^{-1}$ ($760\ Mton\ yr^{-1}$).

The results from simulating the base case scenario suggest that the biofuels industry has an advantage in acquiring advanced biomass feedstocks given current domestic bioenergy policy and ignoring exporters. Referring to the results in Fig. 8, the RIN market incentivizes the biofuels industry to meet RFS targets for the entire simulation. RIN prices start at $0.026\ \$\ l^{-1}$ ($0.10\ \$\ gal^{-1}$) and oscillate around this value until RFS targets plateau in 2022, at which point the RIN price decreases to $0.009\ \$\ l^{-1}$ ($0.035\ \$\ gal^{-1}$). Due to the smoothing effect of the RIN market and biorefinery construction delays, there is a slight overbuild in biofuels capacity during the RFS target plateau, causing the biofuels industry to end the simulation with a 0.7 effective annual capacity factor. The biomass feedstock opens with a $105\ \$\ t^{-1}$ ($95\ \$\ ton^{-1}$) market price and oscillates then decreases to $102\ \$\ t^{-1}$ ($93\ \$\ ton^{-1}$). The biopower sector does not acquire any of the biomass feedstock because no coal plant is willing to pay over $75\ \$\ t^{-1}$ ($68\ \$\ ton^{-1}$) for the feedstock. Exports were purposely excluded from the market by assigning the industry a port value of $66\ \$\ t^{-1}$ ($60\ \$\ ton^{-1}$).

5.2. Incentives to meet all domestic targets

This scenario investigates the added incentives that would be needed for the biofuels and biopower sectors to concurrently meet the production targets assumed in the base case. In that scenario, the biofuels sector settled on a $0.026\ \$\ l^{-1}$ ($0.10\ \$\ gal^{-1}$) RIN price to meet growing RFS targets and the biopower sector had a $15\ \$\ MW\ h^{-1}$ incentive to meet its portion of RPS targets. In the base case scenario, the biofuels sector was able to dominate the bioenergy feedstock market, but the biopower sector remained a non-player because its value for the feedstock was $30\ \$\ t^{-1}$ ($27\ \$\ ton^{-1}$) below the market selling price.

We calculate the additional incentive needed for the biopower industry by forcing it to pay whatever it takes to meet production targets. No assumptions were made about the mechanism behind this additional compliance incentive, and no other changes were made to the base case assumptions. Using this simulation, the difference between the actual cost and the desired cost of production for biopower is the additional incentive that would be needed to meet production targets. Essentially, the biopower industry becomes demand driven instead of price driven in this scenario.

Fig. 9 shows the incentive in addition to the REC value that would be needed for biopower to meet 50% of RPS targets nationwide, and the calculated RIN value in response to the added competition. It is estimated that biopower requires an incentive of 20 to $30\ \$\ MW\ h^{-1}$ in addition to the $15\ \$\ MW\ h^{-1}$ REC price to compete in the advanced biomass feedstock market. If this scenario occurs, it is likely to drive RIN values up to $0.08\ \$\ l^{-1}$ ($0.30\ \$\ gal^{-1}$) over time, which remains under the $0.13\ \$\ l^{-1}$ ($0.50\ \$\ gal^{-1}$) effective cap. Fig. 10 shows the trend in feedstock values, the amount delivered and consumed, and the cumulative demand curves for each industry. Biopower and biofuels both meet their production targets in this scenario, but the market price of the biomass feedstock increases over time from $108\ \$\ t^{-1}$ ($98\ \$\ ton^{-1}$) at the outset to $125\ \$\ t^{-1}$ ($113\ \$\ ton^{-1}$) by 2030.

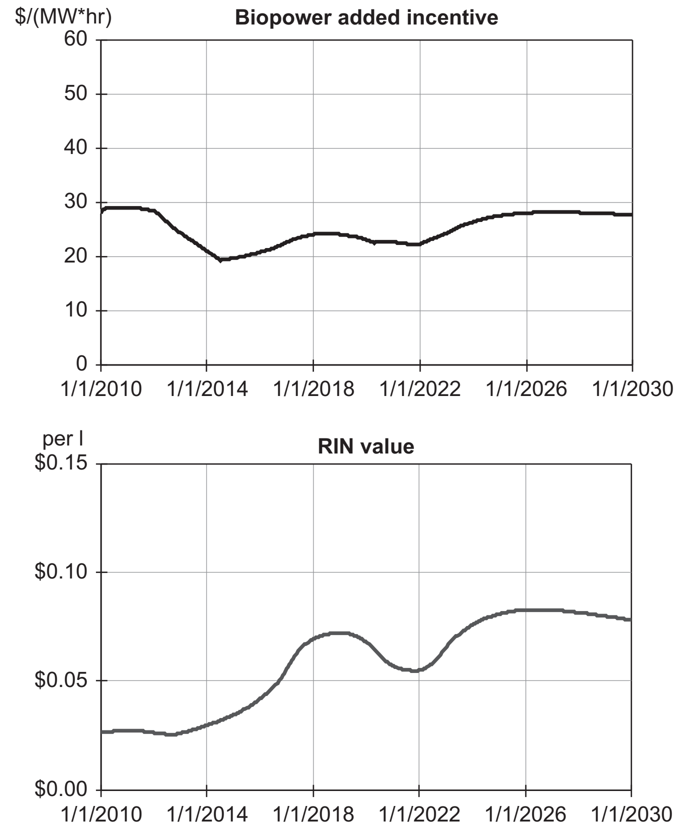


Fig. 9. Calculated added incentive for the biopower industry and dynamic RIN value for the biopower incentives scenario.

5.3. High value for exports

The demand for bioenergy feedstocks in the European Union (EU) has been rapidly increasing in recent years. In 2005, the EU experienced a 16% growth in electricity produced from biomass. In 2010, the demand in the EU for wood pellets increased by 7% to over 11 Mton (Crowe, 2011). North America has doubled its export volume to Europe over the past two years. This growth is expected to continue, which is attracting US industries to expand their production of wood pellets explicitly for export to the EU. To simulate the effect of high value exports, the mean feedstock value to port for export markets was increased from $66\ \$\ t^{-1}$ ($60\ \$\ ton^{-1}$) to $154\ \$\ t^{-1}$ ($140\ \$\ ton^{-1}$). Export quantity demanded is assumed to start at $18\ Mt\ yr^{-1}$ ($20\ Mton\ yr^{-1}$) in 2010 and rapidly increase over the next decade to $320\ Mt\ yr^{-1}$ ($350\ Mton\ yr^{-1}$) by 2024. No other changes were made from the base case for this scenario. Fig. 11 shows that the export sector outbids biofuels for the feedstock during the later years of this simulation. Exporters are able to acquire nearly all the biomass they need to meet overseas demand, while domestic biofuel production does not meet RFS production targets after 2015. This is because the high demand drives feedstock prices up to 140

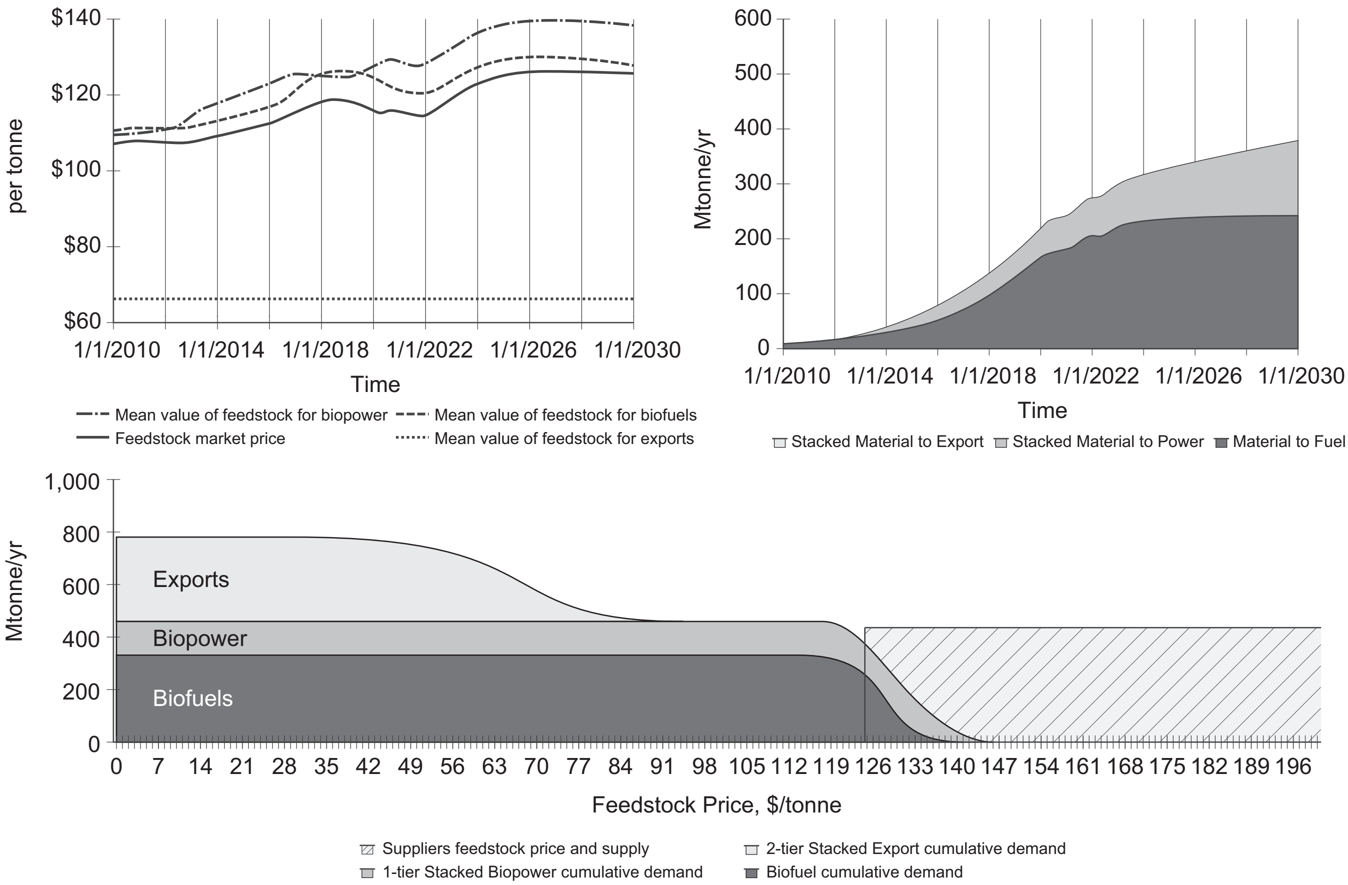


Fig. 10. With incentives oscillating around 40 $ MW h^{-1}, biopower meets 50% of total RPS targets and the feedstock price increases over the span of the simulation.

$ t^{-1} (127 $ ton^{-1}), and RIN values hit the 0.13 $ l^{-1} (0.50 $ gal^{-1}) cap by 2016. The biopower sector continues to have no play in the market under these assumptions.

5.4. Price on GHG emissions

Our policy-driven techno-economic simulations conclude by analyzing the effect of a US GHG emission-limiting policy on the advanced biomass feedstock market. A GHG-limiting policy is simulated that sets a price on GHG emissions per ton of CO_2 equivalent. A recent EIA analysis of S.2191 (America's Climate Security Act of 2007) estimates the effective price of CO_2 equivalent emission at 40 to 60 $ t^{-1} (36 to 54 $ ton^{-1}) to decrease emissions to 15% below 2005 levels (Energy Information Administration (EIA), 2009). Both biofuels and biopower are assumed to be net zero GHG emitters in this case, and therefore receive substantial benefit from such a policy. It is expected that the GHG incentive will provide greater value to the biopower industry than the biofuels industry. With current industry practices, coal emits 2.1 t CO_2 equivalent for every tonne burned, and gasoline emits 0.0024 t CO_2 equivalent for every litre burned (US Environmental Protection Agency (EPA), 2011). With this information, the incentive to the biofuels sector is calculated using Eq. 3:

$$I(P_{\mathrm{GHG}})_{Fuels} = \frac{P_{\mathrm{GHG}} \times EM_G}{GGE_{bf}}, \tag{3}$$

where: P_{GHG} is the effective price of GHG emission [$ t^{-1} (CO_2)]; EM_G the tonne GHG emission per litre gasoline [t (CO_2) l^{-1} (gas)]; GGE_{bf} the fraction gas equivalent of produced biofuel [l (biofuels) l^{-1} (gas)].

Similarly, the incentive to the biopower sector is calculated using Eq. 4:

$$I(P_{\mathrm{GHG}})_{Power} = \frac{P_{\mathrm{GHG}} \times EM_C}{\eta_C}, \tag{4}$$

where: EM_C is the tonne GHG emission per tonne coal [t (CO_2) t^{-1} (coal)]; η_C the efficiency of coal conversion process [MW h t^{-1} (coal)].

Eqs. 3 and 4 were inserted into the Bioenergy Market Model to simulate the addition of a GHG policy to both the base case and the high-value export market case. The lower EIA estimate of 40 $ t^{-1} CO_2 (36 $ ton^{-1}) was used for the effective price of GHG emissions. This price results in a 54 $ MW h^{-1} incentive for the biopower sector and a 0.07 $ l^{-1} (0.26 $ gal^{-1}) incentive for the biofuels sector.

Fig. 12 illustrates the effect of a GHG-limiting policy if exporters do not substantially enter the biomass feedstock market. Both biofuels and biopower meet the assumed production targets in this scenario. In fact, biopower does so with a large margin of feedstock value to spare, suggesting that the industry could expand production beyond the assumed targets. The biofuels industry's RIN value begins at 0.026 $ l^{-1} (0.10 $ gal^{-1}), grows to 0.05 $ l^{-1} (0.19 $ gal^{-1}) by 2018 due to competition with biopower, and shrinks to 0.01 $ l^{-1} (0.04 $ gal^{-1}) by 2022 once RFS targets plateau. Similarly, the market price of advanced biomass feedstocks begins the simulation at 130 $ t^{-1} (118 $ ton^{-1}) and stabilizes at 125 $ t^{-1} (113 $ ton^{-1}) by 2022.

If the 154 $ t^{-1} (140 $ ton^{-1}) value to exporters is assumed along with a domestic GHG-limiting policy, the results in Fig. 13 suggest that domestic consumption of bioenergy feedstocks continues to thrive. The biopower industry retains a significant margin

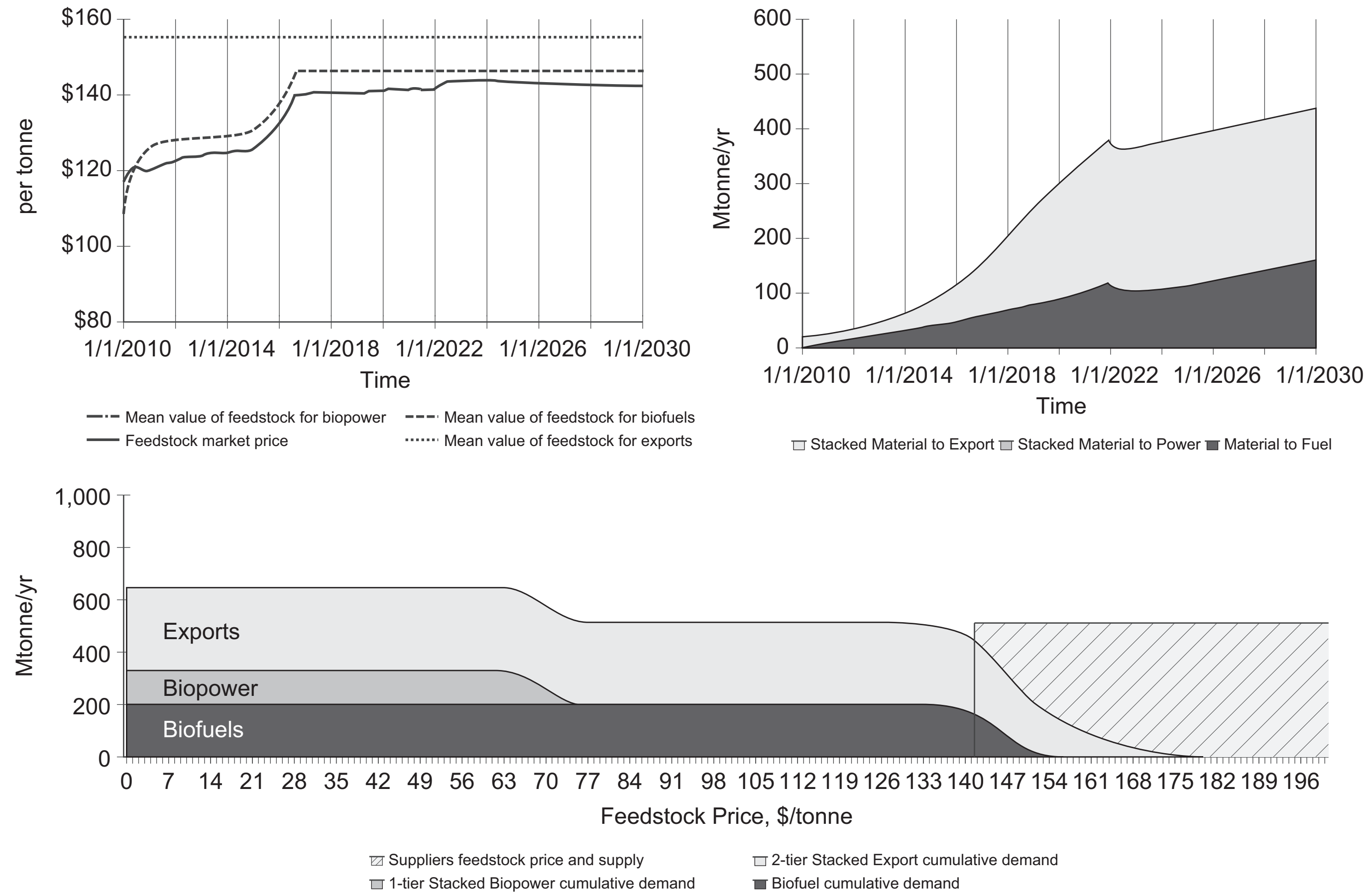


Fig. 11. With high value and demand to exports, biofuels does not meet RFS targets because the RIN value reaches its cap and no longer provides adequate incentive.

of value and is able to meet 50% of RPS targets. The biofuels industry meets RFS targets in most years, but are constrained from years 2015 to 2018 as the RIN value hits the 0.13 $\$\,l^{-1}$ (0.50 $\$\,gal^{-1}$) effective cap. RIN values settle just below 0.10 $\$\,l^{-1}$ (0.38 $\$\,gal^{-1}$) after this time. Exporters are able to acquire 120 t (132 ton) of their 320 t (350 ton) demand in 2030 because their mean feedstock value of 154 $\$\,t^{-1}$ (140 $\$\,ton^{-1}$) is below the final market price of 158 $\$\,t^{-1}$ (143 $\$\,ton^{-1}$) for advanced biomass feedstocks. In all, 490 $Mt\,yr^{-1}$ (540 $Mton\,yr^{-1}$) is supplied by the feedstock grower at the end of this simulation and the grower payment alone is 118 $\$\,t^{-1}$ (107 $\$\,ton^{-1}$).

6. Summary of results

The results of our simulations indicate widely varying behavior for the price of advanced biomass feedstocks depending on policy assumptions. With a 0.13 $\$\,l^{-1}$ (0.50 $\$\,gal^{-1}$) cap on the value of an advanced biofuel RIN, the biofuels industry is able to compete in all scenarios, but does not meet the RFS targets if exporters increase demand significantly. Biofuels maintains a value advantage over biopower in the base simulation for three reasons: liquid transportation fuels are currently valued significantly higher than coal-produced electricity per quantity of energy produced, biofuel production is driven by national policy while biopower production is driven by state policy, and there are few significant alternative transportation fuels for gasoline in the US, but there are several alternatives for coal power. A policy that targets major GHG emitters such as coal fire power plants would disproportionately benefit the biopower industry, to the point that they compete with and even surpass the buying power of biofuels for advanced biomass feedstocks. Exporters may have a large advantage over both industries if no domestic GHG-limiting policy is enacted.

Notably, the second scenario in which the biopower industry receives incentives that cause it to compete with the biofuels industry was also examined by Langholtz et al. (2012). Many of their assumptions are similar to those in this article, and the estimates of cumulative demand from both industries in 2022 are similar: 327 Mt (360 Mton) in our analysis vs. 295 Mt (325 Mton) in theirs. They report a grower payment of 72 $\$\,t^{-1}$ (65 $\$\,ton^{-1}$) to supply this demand, which did not include harvesting and collection costs. The grower payment simulated in our analysis does include harvesting and collection, and is calculated at 78 $\$\,t^{-1}$ (71 $\$\,ton^{-1}$). We also estimated the market price of the processed bioenergy feedstock as 123 $\$\,t^{-1}$ (112 $\$\,ton^{-1}$) in 2022 for this scenario. The additional contributing costs for the feedstock are due to logistics and dynamic supply limitations of the market. This suggests that the grower payment dynamics in the Bioenergy Market Model are reasonable, and that average prices well in excess of 100 $\$\,t^{-1}$ (91 $\$\,ton^{-1}$) for advanced bioenergy feedstocks are not unreasonable.

The primary variable cost that drives up the feedstock price with increasing demand is the grower payment relationship illustrated in Fig. 6. Because this curve is used in an *x*-given-*y* fashion in the Bioenergy Market Model, relatively small slopes indicate relatively high marginal cost of acquiring raw biomass. For example, in 2017 the grower payment curve has a slope of 2 $Mt\,yr^{-1}$ for every 1 $\$\,t^{-1}$ when raw demand exceeds 300 $Mt\,yr^{-1}$. As the simulation moves through time more biomass is available at lower prices, and these slopes become steeper. Fig. 14 provides a dynamic view of this effect. The contours show

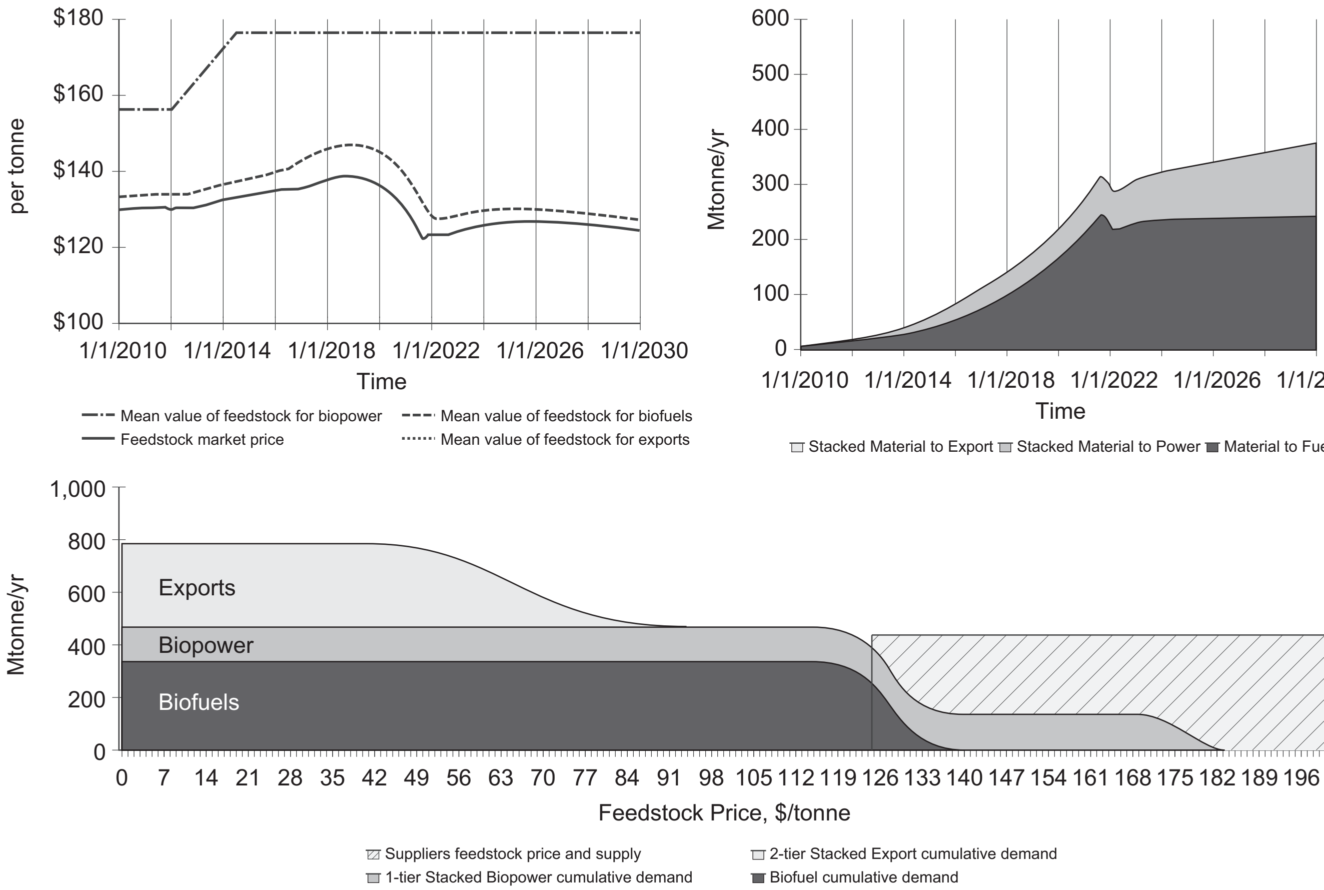


Fig. 12. With a GHG emission limiting incentive, the biopower industry experiences a large increase in its value for biomass.

learning curves for supplying raw biomass for bioenergy feedstocks at different levels of demand. At the end of the simulation in 2030, 500 Mt yr^{-1} (550 Mton yr^{-1}) of raw biomass requires an average grower payment of 95 \$ t^{-1} (86 \$ ton^{-1}) under the base assumptions of the DOE Billion Ton Update (US Department of Energy (DOE), 2011a). However, to satisfy the domestic biopower and biofuels industries and provide biomass to exporters, the volume required in 2030 is 690 Mt yr^{-1} (760 Mton yr^{-1}). These high marginal costs are why the final scenario in which all industries are actively competing exhibits high prices for the bioenergy feedstock, and export demand is not satisfied.

7. Conclusions

This article introduces and demonstrates the use of a computer simulation model to examine bioenergy markets from a strategic policy viewpoint. It shows that multiple policies targeting clean, domestically produced energy can create competition for biomass, and that this competition can effectively drive up prices for the biomass feedstocks and potentially exclude industries from the market. We also show that assumptions about the demand and value for foreign exports have a large effect on whether domestic targets for bioenergy production are met. In general, a GHG-limiting policy similar to the S.2191 Climate Security Act could ensure that the advanced biomass feedstocks being pursued by DOE will stay in the United States to be processed into high-value products. Because the EU already has such policies in place, their economic value for these feedstocks may prove to be much higher and the scenario presented in Section 5.3 in which bioenergy plays a minor domestic role would prove likely. A relaxed cap on RIN values would increase the value of domestic biofuel, but may generate pushback from the biofuels industry.

The Bioenergy Market Model developed for this analysis presents a new method for examining dynamic market pricing for commodities where supply and demand are heavily interdependent. Dynamic supply and demand limitation provide insight into additional market pressures that may drive feedstock prices up. This type of model proves useful for policy studies because it highlights overall system behavior instead of concentrating on fine technical detail. The level of aggregation allows the identification of tipping points, leverage switches, and behavior modes that more detailed analyses often take years to accomplish. GHG-limiting policies and grower payment learning curves have been identified as potential leverage switches in this analysis.

Further work should be done to examine the variable costs present in the logistics of advanced biomass processing to find additional potential leverage switches. Because the grower payment exhibits learning curve behavior, logistics costs may behave similarly. The supplier may have a higher incentive to lower production costs, thereby decreasing the minimum feedstock price if a large body of incremental demand resides below the current minimum price. Therefore, these learning curves could be linked to demand using a feedback loop. As indicated by EIA 2007 report, GHG allowance prices are strongly sensitive to the availability and cost of low-carbon energy technologies. This indicates potential for feedback between bioenergy development and GHG allowance prices, which could be analyzed with the Bioenergy Market Model. Additionally, sensitivity analysis using this model should be accomplished to find technology and policy improvements that have the greatest effect on each industry, which would

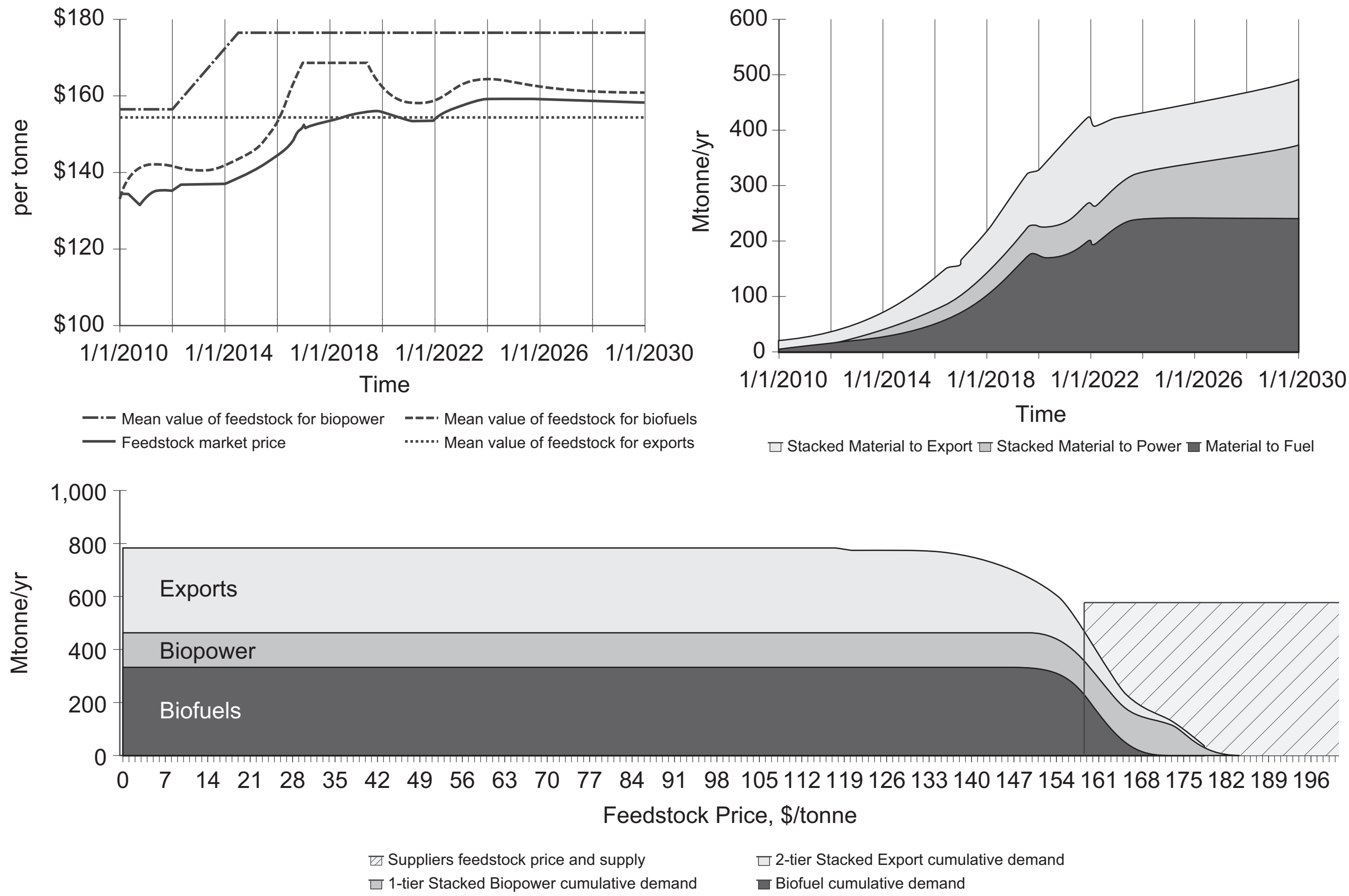


Fig. 13. With a GHG emissions limiting incentive and a powerful export market, domestic targets are still attained, but feedstock prices are relatively high.

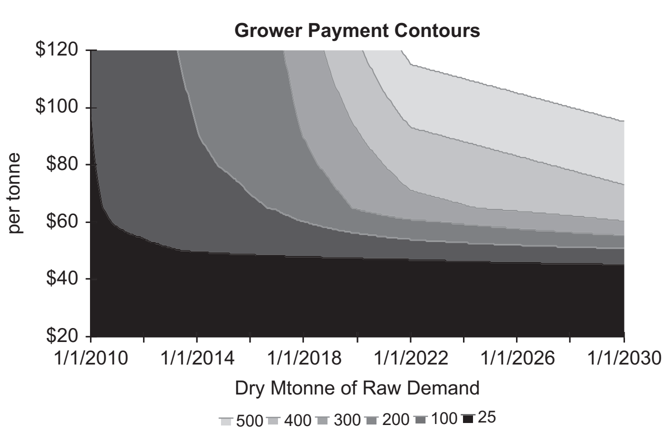


Fig. 14. The grower payment at multiple demand quantities exhibits "learning curve" behavior.

drive research into cost-effective technology improvements. Finally, the model's structure should be used to investigate commodity markets other than those within the bioenergy sector in which technology and policy play a critical role in market performance.

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