Policy Analysis

Modeling Switchgrass Derived Cellulosic Ethanol Distribution in the United States

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Discussions of alternative fuel and propulsion technologies for transportation often overlook the infrastructure required to make these options practical and cost-effective. We estimate ethanol production facility locations and use a linear optimization model to consider the economic costs of distributing various ethanol fuel blends to all metropolitan areas in the United States. Fuel options include corn-based E5 (5% ethanol, 95% gasoline) to E16 from corn and switchgrass, as short-term substitutes for petroleum-based fuel. Our estimates of 1–2 cents per L of ethanol blend for downstream rail or truck transportation remain a relatively small fraction of total fuel cost. However, for even the relatively small blends of ethanol modeled, the transportation infrastructure demands would be comparably larger than the current demands of petroleum. Thus if ethanol is to be competitive in the long run, then in addition to process efficiency improvements, more efficient transportation infrastructure will need to be developed, such as pipelines. In addition to these results, national and regional policy challenges on how to pay for and optimize a new fuel and distribution infrastructure in the United States are discussed.

Introduction

Petroleum has many virtues. It has high energy density, is relatively abundant, is a feedstock for multiple chemicals, and has low cost. Unfortunately, its production, refining, transport, and combustion cause substantial environmental problems. Continued increases in global petroleum consumption will inevitably lead to a shortage and price increases. U.S. fossil fuel use for transportation results in 110 million metric tons of criteria air pollutants emissions (56% increases. U.S. fossil fuel use for transportation results in 110 million metric tons of criteria air pollutants emissions (56% of all U.S. emissions) and 1.9 billion metric tons of carbon dioxide (CO₂) emissions (32% of the U.S. total) (1, 2). Decreasing petroleum consumption by using an alternative—preferably renewable—fuel for use in the light duty (LDV) fleet could address some of these issues.

When made from cellulosic biomass, ethanol can be produced and utilized with no net CO₂ emissions. The production of cellulosic biomass can have many positive impacts in the ecology of agriculture, including increased soil carbon and biodiversity. Since ethanol has 1/3 lower energy density than gasoline, a greater volume of fuel is needed for the same range, but the difference is small for blends with 10–20% ethanol (E10–E20). Ethanol is a liquid, and for the most part is compatible with our current fueling infrastructure.

Numerous studies have addressed the technical and economic aspects of ethanol production including biomass sources and dedicated growth, biomass conversion to ethanol, and to some extent the distribution of ethanol to the retailer (3, 4). Lave and co-workers concluded that ethanol is an attractive fuel and has the potential to become an important alternative fuel if it could be produced in quantity and supplied throughout the country (5, 6).

In this paper we explore possible costs of shipping cellulosic ethanol from production centers to consumers throughout the United States. We assume a robust cellulosic ethanol industry and develop a linear programming model to represent a possible nationwide ethanol distribution system. We consider various levels of ethanol use. In our model only switchgrass is considered as a cellulosic feedstock.

Current Ethanol Infrastructure and the Importance of Cellulosic Ethanol

The United States used ethanol as an alternative to gasoline in 1905 (7). In 2002, 13% of the roughly 490 billion L of gasoline consumed by U.S. light-duty vehicles (LDVs) contained some amount of blended ethanol. However the amount of actual ethanol used by LDVs is small—1.2% by volume and 0.8% by energy (8).

Ethanol is supplied by an industry that consists of more than 90 corn ethanol plants, current or under construction, with an annual production capacity of 17 billion L of ethanol. The industry utilizes 32 million metric tons of corn, about 11% of the U.S. corn crop (9). At average U.S. corn yields of 9 metric ton/hectare in 2003, approximately 4.5 million hectares of corn was required, mainly in the Midwest (10). Corn is transported to the plants by truck and rail. The ethanol produced is shipped for blending with gasoline mainly via truck across the United States.

To fuel the entire U.S. LDV fleet on E10 (blend of 10% ethanol/90% gasoline), 49 billion L of ethanol per year would be needed (Table 1). A complete switch to E100 (100% ethanol required

<table>
<thead>
<tr>
<th>TABLE 1. Ethanol Required to Meet Various Ethanol-Gasoline Blend Levels*</th>
<th>(billion L/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel</td>
<td>required volume of blend</td>
</tr>
<tr>
<td>E5</td>
<td>500</td>
</tr>
<tr>
<td>E10</td>
<td>510</td>
</tr>
<tr>
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<tr>
<td>E85</td>
<td>680</td>
</tr>
<tr>
<td>E100</td>
<td>730</td>
</tr>
</tbody>
</table>

* Base year is 2001, gasoline consumption was 490 billion L of which 6 billion L was ethanol. a HHV for gasoline (35 MJ/L) and ethanol (23 MJ/L) were used for the calculations. c EX denotes the percent by volume of ethanol X contained in the gasoline/ethanol blend. d We have assumed a 19 billion L limit to corn ethanol based on DDGS market limit (see Method); however, if new markets or new products are developed this level could rise.
fuel) would require 730 billion L of ethanol, accounting for the energy differences between gasoline and ethanol.

Corn ethanol production has limits. Corn ethanol production produces a number of coproducts: wet milling—starch, sweeteners, gluten feed, and meal, along with corn oil and dry milling—distiller’s dried grains with solubles (DDGS). Both processes can produce CO₂ for sale. These coproducts offset some of the ethanol production costs (11). Assuming a ceiling for corn ethanol production, due to market saturation of one or more of the coproducts, another source of ethanol will be required to meet the high level demands illustrated in Table 1.

As an emerging technology, cellulosic ethanol production has the potential to meet this additional demand. Although no commercial facilities exist, the technology has moved to pilot stage. Assuming continued development and projected cost reductions, cellulosic ethanol provides opportunities for a wide variety of feedstocks to be used for ethanol production including municipal solid wastes, agriculture and food waste, and energy crops. In this study we focus on energy crops, specifically switchgrass.

In Table 1 we illustrate the potential amounts of cellulosic ethanol needed to meet various levels of ethanol use assuming a 19 billion L (5 billion gallons) ceiling for corn ethanol. The amount of cellulosic ethanol needed will be reduced if corn ethanol production can exceed the level shown here.

On average, fuel use increased annually at a rate of 1.9% from 1991 to 2001 (6). This can be expected to continue unless offset by fuel economy savings. Table 2 shows the ethanol required for various increases of fleet fuel economy. Even at a doubling of fleet average km per L, blends above E10 would likely require ethanol from cellulosic sources. To calibrate the potential for fuel savings via fuel economy improvements, the National Academy of Science’s Committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards found that advanced technologies including direct-injection lean-burn gasoline engines, direct-injection compression-ignition (diesel) engines, and hybrid electric vehicles could improve fuel economy by 20–40% (12). A fleet with higher fuel economy would require a change in the vehicle mix to smaller, lighter vehicles.

Large-scale production of ethanol would require significant investment in feedstock distribution systems, production facilities, ethanol distribution systems, and retail stations. We investigate the implications of a large-scale ethanol industry. We assume that ethanol will be used initially in low-level blends and shift to higher level blends as more cellulosic ethanol becomes available. For low level blends (e.g. E20) both a considerable ethanol delivery infrastructure and the current infrastructure for petroleum transportation will be needed. Two possibilities exist; one, where a duplicate pipeline system will be used for ethanol to capture the most than optimal system, truck and rail, would be used in the short run for ethanol transport until the need for the petroleum pipeline infrastructure diminishes and can be transformed to ethanol use. We examine the downstream transportation freight costs using truck and rail. Since the cost of transporting biomass is relatively high, ethanol plants will need to be located close to low cost biomass resources; the ethanol would be shipped to the major centers of U.S. population and fuel consumption. We develop a linear program to estimate the cost of transportation and the modes of transportation needed to meet the shipping requirements for the current ethanol industry with expanded capacity and scenarios with various amounts of switchgrass-derived cellulosic ethanol added to the fuel mix of the U.S. light duty fleet.

**Methods**

Our transportation optimization model minimizes the shipping distance of ethanol to the 271 largest metropolitan statistical areas (MSAs) from two sources—current corn based facilities (expanded to meet a potential maximum corn ethanol production level) and hypothetical switchgrass cellulosic facilities in the continental United States.

**Transportation Optimization Equations**

Objective Function:

\[
\text{minimize: } \sum_{i=1}^{n} \sum_{j=1}^{m} V_{ij} \times D_{ij}
\]

where \(i\) = export (supply) location (1 to \(n\) number of plants) and \(j\) = import (demand) location (1 to \(m\) number of MSAs).

Constraints:

\[
\sum_{i=1}^{n} V_{ij} \leq E_{j}
\]

\[
\sum_{j=1}^{m} V_{ij} \leq I_{j}
\]

Variables:

Let:

\(I_{j}\) = import (demand) demanded by location \(j\) – (L)

\(E_{i}\) = export (supply) available from location \(i\) – (L)

\(D_{ij}\) = distance between locations \(i\) and \(j\) – (km)

\(V_{ij}\) = volume of ethanol transported between locations \(i\) and \(j\) – (L)

**Estimation of the Variables**

\(I_{j}\): Import (Ethanol Demand) Demanded by Location \(j\). The model considers 271 of the 273 1997 Metropolitan Statistical Areas (MSAs) in the United States, excluding only Anchorage and Honolulu (13). Gasoline demand in these areas is based on the ratio of the MSAs’ population to all of the MSA populations within the state in which the MSA resides. Using state gasoline consumption statistics (14), each MSA’s ratio is used to allocate its demand from the state’s total fuel consumption. Thus, all of a state’s fuel demand is allocated to its MSAs ignoring outlying rural areas. For MSAs crossing state boundaries county level population components (15) of MSAs were used to break the MSAs’ populations into their respective state components.

**TABLE 2. Ethanol Required To Meet Ethanol-Gasoline Blend Levels with Various Fuel Economies**

<table>
<thead>
<tr>
<th>fuel</th>
<th>10%</th>
<th>25%</th>
<th>50%</th>
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<td>290</td>
</tr>
<tr>
<td>E100</td>
<td>660</td>
<td>550</td>
<td>490</td>
<td>360</td>
</tr>
</tbody>
</table>
E. Export (Ethanol Supply) Available from Location i. All new ethanol plants are dry grind mills and produce DDGS as the major coproduct. Milling coproducts offset some of the ethanol production costs (11). Since wet milling production has remained relatively constant over the past 5 years (review of Renewable Fuels Association (RFA) annual reports for the period) we assume that corn ethanol expansion will be limited by DDGS market saturation. Using the industry accepted rule of thumb of 0.8 kg of DDGS per L of ethanol at maximum DDGS sales (14 million metric tons) (16), dry milling will produce 16 billion L of corn ethanol. In 2003 RFA estimated wet milling produced about 3.4 billion L of ethanol, resulting in a combined dry and wet mill production ceiling of approximately 19 billion L.

Year 2002 ethanol plant locations and capacities were obtained from RFA (17). These 78 plants have a total capacity of 12 billion L. We chose to increase the capacity of corn ethanol production to 19 billion L by expanding current facilities. However, since most current corn mills are distributed regionally in the Midwest and new mills would be generally located in the same area, i.e., corn growing regions, this simplifying assumption will have little spatial impact on the national optimization model.

The maximum capacity for any expanded wet mill was limited to 950 million L per year based on the size of most of the largest facilities operated by the large ethanol players, Archer Daniels Midland and Cargill. Dry mill expansions were limited to 190 million L per year based on the observation that only a few plants exceeded this capacity.

For ethanol demand beyond 19 billion L per year, cellulosic ethanol plants using switchgrass feedstock were modeled. Spatial switchgrass availability data were provided by Oak Ridge National Laboratory (ORNL). Assumptions underlying these data can be found in Walsh et al. (18). The switchgrass data were aggregated into 305 POLYSSYS districts (Agriculture Statistical Districts, or ASDs) that are composed of counties having similar attributes (e.g., soil type, moisture, terrain, etc.) and economic conditions. Our scenarios were based on available switchgrass at biomass costs of $33 per metric ton, $39 per metric ton, and $55 per metric ton. The average weighted yields for the data set ranged from 11 to 12 metric tons/hectare.

Ethanol production facilities are assumed to be located where switchgrass is produced. Plant location and size determination was a two-step process. The first step was to determine if an ASD could produce enough switchgrass to support a base plant size of 2000 metric ton/day. This minimum plant size is based on the work of Wooley et al. (19, 20) and Aden et al. (21). Areas that did not meet minimum switchgrass criterion were assumed to produce no ethanol.

In the second step, districts that had more than the minimum amount of switchgrass were assumed to have some combination of various capacity plants that permitted use of all of the available switchgrass in that district. However, modeling was based on a single plant having the capacity to utilize all of the switchgrass available in the ASD. Although ASDs vary in size the resolution of the switchgrass data was at the ASD level preventing spatially locating multiple plants within a single ASD. Since we assumed a robust and commercially viable industry, we assumed all costs related to production (feedstock, feedstock transportation, and conversion costs) permitted the facility to compete in the marketplace.

If an ASD could support at least the base cellulosic ethanol plant feedstock requirement, then a town was chosen randomly within the boundary of the ASD, and all its production capacity was assigned to that town. Even when there was enough capacity to support multiple production facilities within an ASD, only one plant, containing all production, was modeled. Using this method at $55 per metric ton of switchgrass only 137 of the 305 ASDs could support switchgrass based cellulosic ethanol production. At $33 per metric ton, the number drops to 52 ASDs.

At a workshop conducted at Carnegie Mellon University in the summer of 2001, experts agreed that mature process yields would likely be between 330 and 380 L per metric ton of dry switchgrass. We assume the midpoint of that range. 355 L of ethanol per metric ton of switchgrass and using the switchgrass availability provided by ORNL the cellulosic ethanol production facilities would produce approximately 21 billion L of cellulosic ethanol per year at $33 per metric ton switchgrass. This combined with the 19 billion L capacity of the expanded corn ethanol industry would satisfy the capacity requirement of our E5 fuel economy. At $39 per metric ton, 33 billion L of cellulosic ethanol could be produced. This combined with the maximum amount of corn ethanol could provide enough ethanol to meet LDV demand for E10. At $55 per metric ton we expect 70 billion L per year, which would satisfy the requirements for our E16 fuel economy. Higher amounts of ethanol would require higher biomass costs, outside the range of current data so E16 was the highest-level blend modeled.

Dij Distance between Locations i and j. Using the online service MapQuest.com, the distance between cities containing existing corn-based and forecasted cellulosic production facilities to each MSA was compiled into a distance matrix. For the few cases when a specific city/state could not be identified, an approximate zip code was used. Distances between each of the 214 production facilities (78 existing corn based ethanol plants as well as 136 forecasted switchgrass based ethanol plants) and the 271 MSAs were found.

The distances used above are “highway” distances rather than “rail” distances but are used for both transport modes. To test the variance of rail and highway distances, rail distances were taken from Amtrak schedules for all routes offered by Amtrak. When these distances were compared, the distribution of differences between rail and highway distances shows that rail is likely to be longer than highway routes. Thus, our model may underestimate rail distances and ultimately rail shipping costs.

Vij Volume of Ethanol Shipped between Locations i and j. Vij is the optimization model decision variable. The optimization software solves for the optimal set of Vij satisfying the model constraints yielding the minimum L-km shipped throughout the United States. This results in a matrix of Vij (which have been solved for the minimum L-km) that forecasts ethanol shipments between producers and consumers. It should be noted that directly minimizing total shipping costs was not possible due to data limitations concerning fixed and variable costs associated with each mode of transport. Minimizing L-km permits us to estimate the bounds of the cost for each mode of transport (see section Rij Freight Rates between Locations i and j).

Rij Freight Rates between Locations i and j. While not an output of the optimization model, we calculated shipping costs for rail and truck based on the model results. We applied the truck and rail transport costs to the optimization results using the following formula

$$S = R_{mode} \times \sum_{i}^{m} \sum_{j}^{n} (V_{ij} \times D_{ij})$$

where $R_{mode}$ is cost per L-km for truck and rail.

To estimate the values for $R_{mode}$, aggregate total dollars spent on rail and truck transport were taken from the U.S. Bureau of Economic Analysis “1997 Benchmark Commodity by Industry Direct Requirements” table (22). Quantity of commodities shipped by rail and truck between states were taken from the 1997 Commodity Flow Survey (23). Using
United States Geological Survey data which list the geological center of all of the U.S. states (24) and the online “city distance tool” on geobytes.com Web site to calculate great circle distances, a distance matrix was developed which contains the great circle distances between all the geographic centers of all the 48 continental states.

Using the Commodity Flow Survey “Shipments by Destination and Mode of transportation” table for each state-to-state transport, the metric ton-km shipped between individual states was divided by the total metric ton-km shipped nationwide. For example, Alabama’s transportation of goods to Arkansas represents 0.0126% of the national total of all goods transported in the 48 continental states. Thus a matrix of ratios was calculated that captures each state-to-state transportation flow’s fraction of the national total of transportation. This ratio is used to divide the national aggregate dollars spent on rail and truck transport into cost estimates for each respective state-to-state transport. The Commodity Flow Survey also published the amounts transported between states. Dividing each state-to-state cost by the metric tons shipped between states produced a matrix of costs per metric ton shipped. Knowing the distances between state center points, a linear regression was used to produce an equation for cost per metric ton as a function of distance where the slope equals the average cost per metric ton-km.

This procedure was done to estimate the freight rates for truck and rail resulting in rates of $0.15 per metric ton-km ($0.22 per ton-mile) and $0.05 cents per metric ton-km ($0.07 cents per ton-mile), respectively.

For comparison, Eno Transportation Foundation estimates the 2001 truck freight revenue at $0.18 per metric ton-km ($0.27 per ton-mile) (25) and the Association of American Railroads estimates freight railroad $0.02 per metric ton-km ($0.02 per ton-mile), respectively (26).

**Scenarios.** Figure 1 shows a representation of all of the corn and cellulosic switchgrass ethanol facilities and MSAs used in the following scenarios.

As a baseline scenario (Scenario E5 corn) we looked at production of 19 billion L of ethanol solely from corn. Nineteen billion L of ethanol will not meet the requirements for fueling the LDV on E5. Thus not all MSAs would get all of the ethanol they required. In these cases MSAs closest to the production facilities would get their demands met first.

As motivated above, we also modeled three scenarios with low level blends of ethanol—E5, E10, and E16—to fuel the entire light duty fleet, each requiring the use of corn and switchgrass. The availability (spatial and amount) was modeled based on ORNL data for switchgrass costing $33 per metric ton, $39 per metric ton, and $55 per metric ton, respectively. The scenarios were labeled E5-corn/switchgrass, E10-corn/switchgrass, and E16-corn/switchgrass.

**Results and Discussion**

**Switchgrass Availability.** Figure 2 shows available hectares of switchgrass at farmgate prices from $28 to $55 per metric ton used in this study. At an ethanol yield of 360 L per metric ton, switchgrass could provide 1.4–95 billion L. The higher...
value is enough ethanol to supply the LDV fleet with E20 and to meet some expanded fuel consumption due to increasing demand and to develop strategies for hedging against catastrophe.

The estimates of switchgrass availability shown in Figure 2 are sums of the potential switchgrass acreage that could be produced at a given farmgate price. These estimates likely overstate usable switchgrass. For a single plant to be located in any given area, the surrounding land must yield enough switchgrass for its annual needs and be within an economical shipping distance. We determined, for each ASD, whether the available switchgrass provided the minimum amount to support an ethanol production facility. Figure 3 shows the results over a range of farmgate switchgrass prices. At lower amounts of switchgrass ($28 per metric ton) the area growing switchgrass is widely dispersed, and less than half (47%) of the switchgrass is located spatially to supply a facility. At $55 per metric ton, 85% of the switchgrass can be used to supply 2000 metric ton per day facilities, stranding 15% of the potential switchgrass. Of course, smaller sized plants could capture greater amounts of the available switchgrass.

Plant size is a compromise between increased economies of scale and transportation costs for the feedstock. Lynd et al. (3) suggest larger facilities to take advantage of economies of scale and provide ethanol at prices equivalent to or lower than gasoline on an energy basis. However, a complete adoption of such a strategy would have the downside of "stranding" ever-greater amounts of the biomass limiting further the potential of cellulosic ethanol to displace gasoline.

**Providing 19 Billion L of Ethanol to the MSAs from Corn.**

We modeled the transportation from the current ethanol plants with an expanded ethanol production of 19 billion L to the MSAs whose total demand was based on E5 consumption. The optimization minimizes transportation distance so the closest demand will be met first. Figure 4 shows the MSAs and production locations (corn ethanol facilities) used in scenario E5-corn. Most production facilities are located in the upper Midwest, while most demand is located along the coasts (East, West, and Gulf), Great Lakes, and throughout the Southeast. The optimization results in average shipping distance from these plants to the MSAs of 1030 km (Table 3). The volumetrically weighted shipping distance (accounting for total L of ethanol shipped) was 1100 km. The difference suggests that there are some volumes of ethanol being shipped distances much greater than the average. In addition, not all demand is met: only 82% of the MSAs receive the required ethanol. In fact 45 of the 271 MSAs received no ethanol at all, and 6 received only partial shipments. These MSAs were all located along the east and west coasts. The centroid of production (the geographical center of all ethanol...
production facilities) and consumption (the geographical center of all MSAs receiving ethanol) in the scenario were located in west-central IA and southeastern MO, along the Mississippi River, respectively.

If all the shipments in scenario E5-corn were made by truck the average cost would be $0.13 per L ethanol. If all shipments were made by rail, then the cost would be reduced to $0.05 per L. This would add $0.01 and $0.002 per L of E5 blend at its destination, respectively.

Note that if the corn ethanol industry ultimately produced an amount of ethanol greater than the 19 billion L modeled here, then the additional ethanol would be shipped to meet the unfulfilled demand in scenario E5-corn. However, these changes would likely be minor since new mills would be generally located in the same geographic region as the current mills.

Providing E5 from Corn and Switchgrass. To provide enough ethanol to meet the entire fleet demand for E5, cellulosic ethanol needs to be produced. The addition of 51 cellulosic plants producing an additional 8 billion L of ethanol was modeled. Figure 5 represents the MSAs and production locations (corn and switchgrass ethanol facilities). All new cellulosic ethanol plants were located in the Southeast. Even though switchgrass could be produced throughout the Midwest, the model chose locations that were closest to ethanol demand minimizing shipping distance.

The summary data for this scenario are also shown in Table 3. In scenario E5-corn/switchgrass all MSAs’ ethanol demands were met. Compared to scenario E5-corn the average distance between MSAs receiving ethanol was reduced by about 4%. However, the volumetrically weighted average remained virtually unchanged. As can been seen in Figure 5 the centroid of production moved into northern Missouri, reflecting the “new” cellulosic ethanol plants located throughout the Southeast, while the centroid for consumption shifted only slightly to the southwest. The movement of the center of consumption is reflected in the fact that all MSAs, including those along the coasts that did not receive ethanol in the E5-corn scenario, received their demanded ethanol; more ethanol was shipped in the E5-corn/switchgrass scenario longer distances. The total cost of shipping by rail or truck increased from scenario E5-corn as expected because of the increase in ethanol production, but the cost based on an E5 blend remained essentially unchanged.

Providing E10 and E16 from Corn and Switchgrass. Switchgrass has, potentially, a broader geographic growth range than corn, ranging throughout the eastern half of the United States. In scenario E10-corn/switchgrass and scenario E16-corn/switchgrass, switchgrass becomes the major source of ethanol. Figures 6 and 7 show the distribution of

<table>
<thead>
<tr>
<th>parameter</th>
<th>scenario</th>
<th>19 billion L - corn</th>
<th>fleet wide E5 use - corn/switchgrass</th>
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<tr>
<td>% MSAs with demands met</td>
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<td>100</td>
</tr>
<tr>
<td>% overall demand volume met</td>
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<td>100</td>
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<td>av weighted shipping distance (km)</td>
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<td>total costs (billion $)</td>
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FIGURE 5. Location and size (production or consumption) of ethanol production facilities (corn) and MSAs receiving ethanol for scenario E5-corn/switchgrass. Note: Geographical centers of consumption and production are included (centroids).
switchgrass cellulosic ethanol production facilities and MSAs for each scenario. The data from these optimizations are shown in Table 4. In scenario E10-corn/switchgrass there were 153 "production facilities" compared to 78 and 129 in the previous two scenarios. Comparing Figures 5 and 6 shows the more widely dispersed ethanol production plants in scenario E10-corn/switchgrass compared to scenario E5-corn/switchgrass. The centroid of ethanol production moved slightly northwest and away from the centroid of ethanol consumption. The centroid movement and the wider distribution of the plants are reflected in the increase in the average shipping distance and decrease in the average weighted distance, respectively, compared to the E5-corn scenario. On a per L basis of E10 the transportation costs would increase the total costs by a half a cent to a cent compared to gasoline.

E16-corn/switchgrass (Figure 7 and Table 4) adds an additional 83 cellulosic ethanol production facilities bringing the total to 212 corn and cellulosic ethanol plants. As expected, due to the widest ethanol plant distribution and the closest approach of the two centroids (production and demand) the E16-corn/switchgrass provides the lowest shipping distance 930 km and the lowest weighted shipping distance, 1000 km, of all scenarios. Transportation costs per L decreased to $0.12 and $0.04 for truck and rail. On a blend basis this would increase the cost of E16 to between 1 and 2 cents per L for truck and rail transportation.

Impact of Ethanol and Switchgrass Yields on Model Results. The scenario results are dependent on the ethanol yield (ethanol produced per unit of switchgrass) and switchgrass yield (amount of switchgrass produced per area of land planted). Both affect the volume of ethanol available to meet demand but in slightly different ways.

In our model we assume all plants use the same technology. In switchgrass scenarios ethanol demand has been met. Adding additional ethanol production capacity (increasing ethanol yield) permits plants close to MSAs to increase ethanol shipments with a concomitant reduction from more distant ones. The result would be a reduction in the average shipping distance, the average weighted shipping distance, total ethanol shipping cost, and average cost per L. Alternatively, the increased production could go to achieving higher ethanol gasoline blends (not modeled). Such a scenario would increase the total shipping costs due to higher ethanol volumes shipped. The other parameters would remain unchanged.

In our model increasing switchgrass yields will increase yields in each ASD incrementally. This is an extreme simplification because the ORNL model that produced the underlying spatial switchgrass data has complex interactions between yield and climatic/soil data as well as interactions with other commercial corps planted in any particular ASD. Given the spatial switchgrass data used here, increased switchgrass yields could have two impacts. (1) In ASDs having ethanol production capacity, increasing the availability of switchgrass increases the amount of ethanol that can be produced. The impact on ethanol transportation would be similar to that described for increasing ethanol yield. (2) Increasing switchgrass yields in ASDs that previously did not have enough switchgrass to supply a 2000 metric ton/day facility might now exceed this threshold increasing the total number of production plants in the model. For instance, doubling the yield in scenario E16 corn/switchgrass would result in 54 additional plants producing at least an additional 13 billion L of ethanol. These new plants would be distributed throughout the Midwest and East. More than 75% would be located near demand centers suggesting an overall reduction in shipping costs.

Ethanol Transportation. The oil industry ships 6.4 billion L of petroleum and petroleum products each day in the
United States. Sixty-six percent of these shipments occur by pipeline (27). The remainder is via ship and barge (28%), truck (4%), and rail (2%). There is an extensive pipeline system for moving petroleum and petroleum products comprising 320,000 kilometers of crude and product lines. Pipelines are the most cost-effective method for shipping liquid products; the cost of shipping a liter of gasoline from Houston to New York (over 2,400 km) is only $0.008 or about $0.004 per metric ton-km (27). Ideally as the ethanol industry expands, pipelines would become the dominant mode of transportation for finished product. Much of the existing petroleum pipelines could be converted to ethanol transport. However, for ethanol use in low-level blends, such as E16, there will remain considerable demand for gasoline and its delivery infrastructure. Coshipping ethanol and gasoline, either neat or as a gasoline-ethanol, is incompatible due to the presence of water in petroleum product lines. Thus there would be little excess pipeline infrastructure available for any significant ethanol delivery until ethanol becomes the dominant portion of the transportation fuel mix. Until that point, ethanol shipping would be dominated by truck and rail shipments. The use of unit trains and inventive designs incorporating a combination of truck and rail use would lower cost below what is shown in this study.

As a comparison, the average cost of shipping crude oil from field to the refinery contributes $0.01 per L to the gasoline price (Table 5). The shipping cost of gasoline from refinery to consumer is, on average, $0.003 per L. The total

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### TABLE 4. Optimization Results for Supplying E10 and E16 to MSAs

<table>
<thead>
<tr>
<th>parameter</th>
<th>scenario E10 - corn/switchgrass</th>
<th>scenario E16 - corn/switchgrass</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSAs with demands met (% of total)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>overall demand volume met (% of total)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>av shipping distance (km)</td>
<td>990</td>
<td>930</td>
</tr>
<tr>
<td>av weighted shipping distance (km)</td>
<td>1080</td>
<td>1000</td>
</tr>
<tr>
<td>shipping truck total costs (billion $)</td>
<td>6.7</td>
<td>10.1</td>
</tr>
<tr>
<td>av cost ($/L)</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>av cost ($/L of blend)</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>shipping rail total costs (billion $)</td>
<td>2.2</td>
<td>3.4</td>
</tr>
<tr>
<td>av cost ($/L)</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>av cost ($/L of blend)</td>
<td>0.005</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### TABLE 5. Costs Components of Gasoline and E16 ($/L)

<table>
<thead>
<tr>
<th>component</th>
<th>gasoline</th>
<th>cellulosic E16</th>
</tr>
</thead>
<tbody>
<tr>
<td>feedstock (gasoline/biomass)</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>transportation (to refinery)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>refining</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>transportation (to retail)</td>
<td>0.003</td>
<td>0.02</td>
</tr>
<tr>
<td>retail</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>taxes</td>
<td>0.11</td>
<td>0.1</td>
</tr>
<tr>
<td>total</td>
<td>0.39</td>
<td>0.43</td>
</tr>
</tbody>
</table>

*Gasoline costs were adapted from Credit Suisse First Boston (28).

*The cost data are derived from ref 19 for 2015 case. The cost of feedstock was changed from the assumed $28 per metric ton to $55 per metric ton, and transportation cost for biomass from farmgate to refinery gate was assumed to be $5 per metric ton. Taxes were assumed to be revenue neutral. Since the use of E16 would require greater "liters" to provide the same energy as gasoline, the taxes were decreased to provide taxing authorities constant revenue.
transportation cost is less than 2% of the overall price of a L of gasoline. The ethanol transportation costs for E16 on a per L of blend basis were estimated above as high as $0.02 per L, assuming all transportation from production site to consumer was via the most expensive mode, truck. This is only 5% of the total predicted price ($0.43 per L) for E16 - still a low portion of the overall price of fuel.

**Impact of Ethanol Use.** Increased use of ethanol could have positive security and environmental impacts. For instance, use of E20 would reduce gasoline consumption by 42 billion L per year or about 11% (Table 1). This is equivalent to 110 million L of oil per day or about a 4% reduction in U.S. petroleum use. At the margin, this would lead directly to a reduction in imports of 7%, likely moderating world petroleum prices.

Wooley et al. (19) estimate the capital costs for the production of a L of ethanol to range from $0.92 per L to as low as $0.48 per L with future process improvements. Using the low value for costs and the highest level of cellulosic ethanol production we modeled, the 68 billion L of cellulosic ethanol for E16 would require $34 billion in cellulosic ethanol plant investments. The expansion of corn-based ethanol would add another $2.5 billion dollars to the total infrastructure cost. Plant capital costs are likely to be the largest single cost component of the ethanol supply chain. For instance even if all transportation of ethanol was accomplished by truck, which is not likely (see below), we estimate the total capital costs using all new tanker trucks would be on the order of $1.6 billion. If ethanol were transported by a duplicate pipeline system, which we did not model, similar to that which is currently in place for petroleum product distribution, the capital cost would be on the order of $23 billion.

Although our study is limited to E16, more switchgrass could be available at higher farmgate prices making higher levels of ethanol possible. We assume, however, that there will be limits to these supplies due to competition with food crops. Additional sources of cellulosic ethanol would likely come from agricultural residues, forest residue, and municipal solid wastes (29). Corn stover alone could provide an additional 87 billion L of ethanol. This is an upper bound estimate and assumes 100% utilization, which is unlikely. Also, as we showed with switchgrass, the spatial distribution will probably limit this estimate to a lesser amount. Other options exist to expand the use of ethanol including the import of ethanol from countries such as Brazil.

With the use of ethanol—and cellulosic ethanol in particular—comes a reduction in CO2 emissions through the replacement of a fossil fuel with a renewable fuel. MacLean and Lave (30) reviewed the life cycle studies addressing this issue from wells to tank. On average gasoline generated 15–26 g CO2 equivalent/MJ of fuel. Corn and cellulosic derived ethanol produces – 19 to 20 and –85 to +14 g CO2 equivalent/MJ, respectively. Using the midpoints of these values E16 could reduce CO2 emission from the light duty fleet by 39%. Going to E85 the reduction would be on the order of 180%.

Our results suggest that corn and cellulosic ethanol—at least in the short run—can be produced and distributed at a modest premium to gasoline distribution costs and provide domestic economic, environmental, and energy security benefits. However the total infrastructure requirements, not the unit costs, are problematic. A key issue is the geographic relocation from refineries on the coasts to facilities in the interior of the United States. Hundreds to thousands of production facilities, costing up to a half a trillion dollars, would be required to replace our 150 petroleum refineries.

The E16 scenario modeled would require roughly 73 billion metric ton-km of product to be shipped. If moved by truck, it would add 5% to current truck movements in the United States for what is only a niche solution (and about 3% if done by rail). Thus, for both cost and freight efficiency reasons pipelines become important. But we will then be faced with the tough short-term policy decision of whether to build almost $25 billion of ethanol pipelines just to make petroleum pipelines obsolete in the long-term.

National level solutions—needed to spur innovation and normalize vehicle and fuel requirements—actually increase overall shipping distances, while regional solutions such as ethanol in the Midwest could be done inexpensively and quickly, with modest infrastructure pressures.

As suggested above, some of the transitions to an ethanol economy can be incremental and adjusted to moderate social and infrastructure costs. Improvement of fuel economy standards in lockstep with such decisions could be a win–win scenario. But in the end, the decision of how best to pursue alternative fuels and infrastructure remains challenging and capital intensive.

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