

Economic and Environmental Transportation Effects of Large-Scale Ethanol Production and Distribution in the United States

HEATHER L. WAKELEY,[†]
CHRIS T. HENDRICKSON,^{*,‡}
W. MICHAEL GRIFFIN,^{§,⊥} AND
H. SCOTT MATTHEWS^{‡,§}

Departments of Civil and Environmental Engineering and Engineering and Public Policy, and Tepper School of Business, Carnegie Mellon University, Pittsburgh Pennsylvania 15213 and TRC Energy Services, Ithaca, New York 14850

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The combination of current and planned 2007 U.S. ethanol production capacity is 50 billion L/yr, one-third of the Energy Independence and Security Act of 2007 (EISA) target of 136 billion L of biofuels by 2022. In this study, we evaluate transportation impacts and infrastructure requirements for the use of E85 (85% ethanol, 15% gasoline) in light-duty vehicles using a combination of corn and cellulosic ethanol. Ethanol distribution is modeled using a linear optimization model. Estimated average delivered ethanol costs, in 2005 dollars, range from \$0.29 to \$0.62 per liter (\$1.3–2.8 per gallon), depending on transportation distance and mode. Emissions from ethanol transport estimated in this work are up to 2 times those in previous ethanol LCA studies and thus lead to larger total life cycle effects. Long-distance transport of ethanol to the end user can negate ethanol's potential economic and environmental benefits relative to gasoline. To reduce costs, we recommend regional concentration of E85 blends for future ethanol production and use.

Introduction

U.S. ethanol production capacity grew at an annual rate of 32% from 2005 to 2008 (1), an order of magnitude greater than the rate of increase in gasoline consumption (2, 3). Existing and planned ethanol production capacity in the U.S. is 50 billion L/yr (13 billion gal/yr) (4), equivalent to 7% of 2006 light-duty gasoline consumption, calculated on an energy basis (5). The Energy Independence and Security Act of 2007 (EISA) requires the use of 136 billion liters (36 billion gal) of fuel produced from renewable biomass by 2022 (6). The rapid growth of ethanol production and use in the U.S. has major infrastructure implications. In addition to the construction of additional production capacity, transporta-

tion of feedstock to biorefineries and of ethanol to markets will result in an increase in transport demand. Ethanol will be primarily produced in the midwest and will need to be transported long distances to major demand centers on the coasts. Increases in ethanol production will result in shifting transportation demand for corn, biomass feedstocks, ethanol, and byproduct, which will affect rail, barge, and truck transportation. The growth of the ethanol market and transportation demands must also compete with significant growth in other major freight transport categories (7).

A primary motivation to expand ethanol use is to reduce dependence on foreign imports of petroleum through domestic ethanol production. Ethanol can also provide an economic advantage. Rising petroleum costs, as well as defense expenditures to protect foreign interests, can make ethanol a cost-effective option. A third motivation for producing biofuels is to decrease greenhouse gas (GHG) emissions. In order for renewable fuels to be counted under the EISA mandate, they must have at least a 20% reduction in life cycle greenhouse gas emissions, as compared to baseline 2005 gasoline emissions (6).

In late 2007, the US Department of Agriculture (USDA) published a report assessing transportation issues facing the growing ethanol market (8). They predict that demand for truck transport in the agricultural sector will increase, and rail and barge demand may decrease if corn exports decrease. Ethanol and its byproducts must compete with total demand for freight transport, which is rapidly increasing due to consumption of imported goods and the need to get them to local markets (8). Morrow completed an economic study of the distribution of corn and switchgrass-derived cellulosic ethanol throughout the U.S. with a focus on low-level blends, up to E16 (16% ethanol, 84% gasoline) (9). The study indicated that ethanol transport costs in an optimized system, at \$0.02/L of E16, are an order of magnitude greater than equivalent transport costs for gasoline, at \$0.003/L. This paper builds upon that work, considering effects of feedstock prices and transport on ethanol production costs, national distribution of a high-level blend for three production scenarios, and environmental impacts by presenting a comparative analysis for nationwide production and distribution systems of corn and cellulosic ethanol in the U.S.

The goal of this analysis is to characterize costs and environmental implications for the distribution of E85 (85% ethanol, 15% gasoline) as a substitute for a portion of U.S. gasoline demand. E85 is used in this analysis, as it is the highest blend that can be used in current flex-fuel vehicles (10). Three different scenarios are investigated in this study (Table 1). The first, *Near Term Corn Ethanol*, is a baseline scenario that considers the production and distribution of 57 billion liters (15 billion gal) of corn ethanol, corresponding to current mandated upper limit of corn ethanol production in the U.S. (6). Existing and planned capacity of 50 billion L/yr is uniformly expanded to reach this limit. This amount of fuel production represents 8% of light duty gasoline consumption in 2006, calculated on an energy basis. The second scenario, based on the EISA Biofuel Mandate for 2022, considers the production and distribution of 136 billion liters of ethanol, with 57 billion liters of corn ethanol. For this analysis, it is assumed that the remainder is supplied by cellulosic ethanol produced from switchgrass, though the mandate requires only 60 billion liters of cellulose while the remainder could come from other advanced biofuels. The final scenario considers large-scale production of

* Corresponding author phone: 412-268-1066; e-mail: cth@cmu.edu.

[†] TRC Energy Services.

[‡] Department of Civil and Environmental Engineering, Carnegie Mellon University.

[§] Department of Engineering and Public Policy, Carnegie Mellon University.

[⊥] Tepper School of Business, Carnegie Mellon University.

TABLE 1. Ethanol Production and Distribution Scenarios Evaluated

scenario	corn ethanol (billion L)	cellulosic ethanol (billion L)	petroleum displacement ^a	FFVs required (million) ^b
near-term corn ethanol	57	0	8%	25
ESIA 2022 mandate	57	80	19%	60
large-scale cellulosics	57	210	36%	120

^a Based on 2006 light duty gasoline consumption (5).

^b Assuming a fuel economy of 20 mpg, 12 000 mi/yr and that FFVs are operated exclusively on E85.

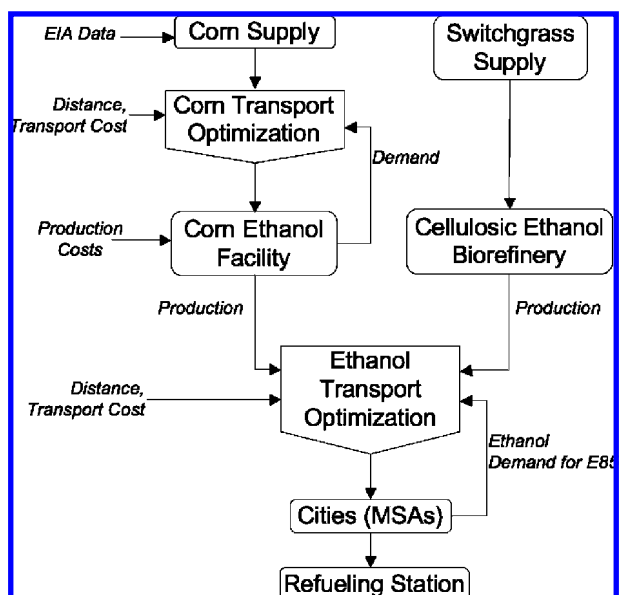


FIGURE 1. Ethanol Distribution Model.

cellulosic ethanol, for a total of 268 billion liters (70 billion gal) of ethanol.

Data Sources and Methods. The methods and assumptions used to estimate transportation requirements and costs for each scenario are discussed below and the model illustrated in Figure 1, where data flows are noted in italics. Additional detail on the modeling procedures and assumptions can be found in the Supporting Information (SI).

Spatial Data for Corn and Switchgrass Production. Spatial data for corn and switchgrass production through 2030 were obtained from the U.S. Energy Information Administration (EIA). The data were calculated by EIA using the policy analysis system (POLYSYS) model, a national simulation model for the U.S. agriculture sector which has the ability to estimate impacts resulting from policy, economic, resource, or environmental changes (11). POLYSYS allows the interaction of agricultural supply, demand, and income through modules (12). The interdependent modules simulate crop production for 305 POLYSYS regions in the U.S., analogous to agricultural statistical districts (ASDs) (13).

POLYSYS has been used to analyze the impacts of large-scale energy crops, including corn, switchgrass, corn stover, wheat straw, and forest trimmings and residues (14–16). The EIA feedstock data set provided locations for corn and switchgrass production. Three feedstock scenarios were chosen from the data set, one for each of the ethanol production scenarios in this study. A sensitivity analysis was completed to determine the effect of different spatial

feedstock distributions on study conclusions. The choice of scenarios and sensitivity analysis are discussed in the SI.

Corn Ethanol Production. The corn ethanol production capacity used as a basis for all three scenarios is the maximum in the *EISA mandate*, 57 billion L/yr (6). Existing and proposed capacity as of late 2007 is 50 billion L/yr at 195 facilities (4), requiring a uniform 12% increase in existing and planned capacity. Over 93% of this additional capacity is located in the Midwest. This calculation is discussed further in the SI.

A linear optimization model was constructed in order to allocate corn from the ASDs to the ethanol facilities. The model minimizes the total system cost by determining the amount of corn from ASD *i* that is transported to facility *j*. The following objective function for rail transport of corn is minimized with respect to m_{ij} :

$$\sum_i \sum_j (m_{ij} C_i + 1.52 R d_{ij} m_{ij})$$

where m_{ij} = quantity of corn transported from ASD *i* to facility *j* (metric ton), C_i = cost of corn at ASD *i* (\$/metric ton), R = cost of rail transport (\$/metric ton-km), d_{ij} = great circle distance from ASD *i* to facility *j* (km), 1.52 = rail circuitry factor (17). Subject to

$$\sum_j m_{ij} \leq M_i$$

$$\sum_i m_{ij} \geq Q_j$$

where M_i = corn available at ASD *i* (metric ton), Q_j = corn demand at facility *j* (metric ton), Cash operating costs and byproduct credits for ethanol production are based on a 2002 USDA survey of ethanol production costs (18). Kwiatkowski (19) presents similar results from modeling effects of parameter changes on production costs.

Cellulosic Ethanol Production. Cellulosic ethanol production from switchgrass is included in the *EISA 2022 Mandate* and *Large-Scale Cellulosic* ethanol scenarios, assuming a yield of 420 L of ethanol per metric ton switchgrass (100 gal/ton) (20, 21). Cellulosic ethanol biorefinery capacities were assumed to range from 2000 to 10 000 t/day, determined by switchgrass availability in a given ASD (22, 23). Since there are no industrial-scale biorefineries currently in operation in the U.S., it was assumed that they would be colocated with switchgrass production to reduce biomass transportation costs. Biorefinery size is eventually limited by increased biomass transport costs. The greater the feedstock requirements, the greater the area required to provide those feedstocks, thus leading to higher transportation costs (22). Multiple biorefineries were assigned to ASDs that could supply more than 10 000 t/day switchgrass, with capacity divided evenly. There are 100 and 180 biorefineries created for the *EISA 2022 Mandate* and *Large-Scale Cellulosic* scenarios, respectively, assumed to be located at ASD centers. Switchgrass is assumed to be transported by truck. Truck transport costs are estimated using the same method as for corn transport.

Costs of cellulosic ethanol production have been estimated in previous studies, though there is little experience with large scale production (21–23). Nonfeedstock production costs at the biorefinery, including other raw materials, overhead, and taxes, were estimated from Aden (22).

Fuel Demand. The entire U.S. fuel demand was assumed to be located in the largest cities, or metropolitan statistical areas (MSAs), in the continental U.S. Eighty percent of the U.S. population is located in the 268 MSAs with a population greater than 140 000 (24, 25).

A second optimization model was used to allocate ethanol from production facilities to the MSAs, minimizing total costs.

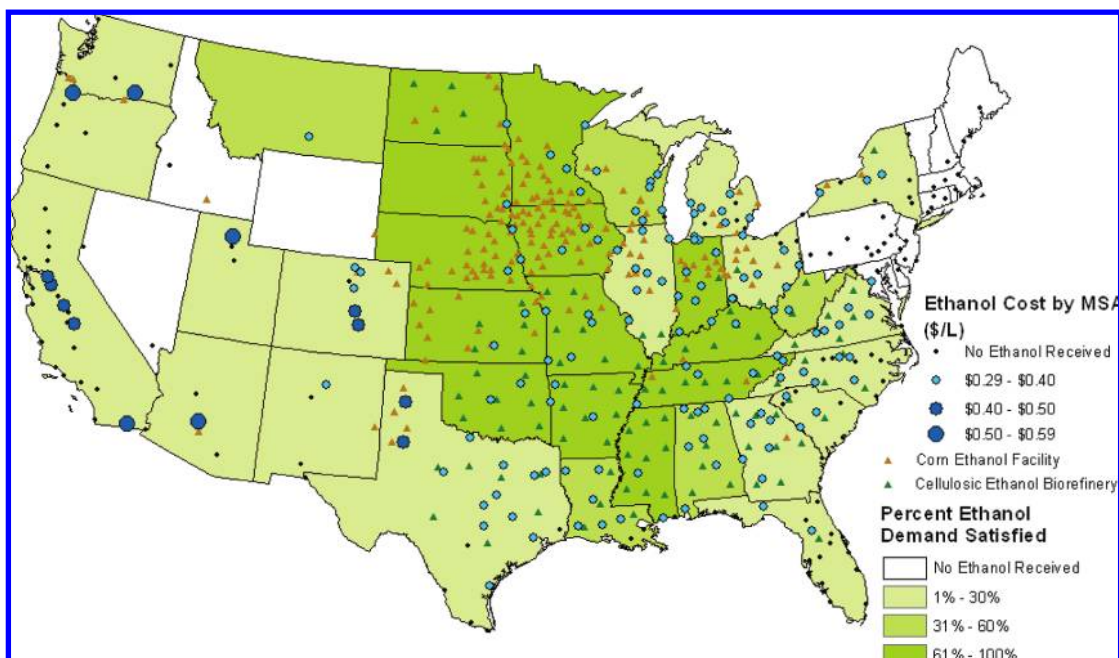


FIGURE 2. Distribution and delivered cost of 57 billion liters of corn ethanol and 80 billion liters of cellulosic ethanol for EISA 2022 Mandate scenario.

Inputs to the model include the cost of ethanol leaving each facility gate (including feedstock and production costs) and costs for rail or truck transportation. Ethanol transport in this study is limited to these two modes as they currently account for 90% of ethanol produced in the U.S., with barges making up the remainder. Average transportation rates are assumed with no congestion effects or volume shipment discounts. It is assumed that at distances less than 400 km (250 mi), distribution by truck is preferred due to several logistical concerns (18). The most significant factor in this decision is that trucks offer more flexibility to transport ethanol according to market demand, greatly reducing storage requirements at the biorefinery (8). The linear optimization model is constructed to minimize the total system cost by determining the amount of ethanol from facility j that is transported to MSA k . The objective is to minimize the sum of the following functions with respect to q_{jk} :

Minimize

$$\sum_j \sum_k (C_j + F_{jk}d_{jk})q_{jk}$$

where

$$F_{jk} = \begin{cases} 1.23T & \text{If } d_{jk} < 400\text{km} \\ 1.52R & \text{If } d_{jk} \geq 400\text{km} \end{cases}$$

q_{jk} = quantity of ethanol transported from facility j to MSA k (L), C_j = facility gate cost of ethanol at facility j (\$/L), T = cost of truck transport (\$/L-km), d_{jk} = great circle distance from facility j to MSA k (km), and 1.23 = truck circuitry factor (17)

Subject to

$$\sum_k q_{jk} = Q_j$$

$$\sum_j q_{jk} \leq D_k$$

where Q_j = ethanol available at facility j (L) and D_k = ethanol demand for E85 at MSA k (L).

Greenhouse Gas Emissions from Transportation. The economic input-output life cycle assessment (EIO-LCA) model was used to quantify total life cycle emissions from truck and rail transportation in this study (26–28). Transportation costs from the optimization models were converted to 1997 dollars, to determine emissions using the rail and truck transportation sectors of the EIO-LCA model. Results are compared to published ethanol LCA studies.

Results and Discussion

Estimated Ethanol Costs. Ethanol costs and distribution results from the *EISA 2022 Mandate* scenario are shown in Figure 2. Ethanol received, as a percentage of demand by state, is indicated by shading. Of 268 MSAs in this least-cost scenario, 74 received 100% of the ethanol demand, 70 received partial shipments, and 124 did not receive any ethanol. Cities on the east and west coasts, furthest from ethanol production, receive little or no ethanol. Results and figures for the *Near Term Corn* and *Large-Scale Cellulosics* scenarios can be found in the SI.

There is little variation in corn transport among the three scenarios, indicating that switchgrass production for ethanol is not likely to affect the distribution of corn production. Estimated average corn transport distances are 130 and 110 km for rail and truck transport, respectively, and range from 10 to 2000 km. The corresponding average transport costs are \$0.01/L and \$0.04/L. Truck transport is dominant in Iowa (29), however facilities with corn transport distances of more than 400 km (250 mi) are likely to use rail due to the cost difference. Subsequent costs presented in this paper assume rail transport. The majority of the corn ethanol facilities are located near sufficient corn supply, but corn transport distance for four (out of 195) facilities is greater than 1000 km (620 mi).

Transport distances for switchgrass are similar for the *EISA 2022 Mandate* and *Large-Scale Cellulosics* scenarios due to assumptions in biorefinery placement. Estimated average distances are 60 km, with a cost of \$0.02/L. Transport distances are a function of ASD area and range from 30 to 140 km. Though the total amount of switchgrass varies between the two scenarios, the distribution of switchgrass production is similar.

TABLE 2. Corn and Cellulosic Ethanol Distribution Requirements by Scenario

	average distance(km)	average cost ^a (\$/L)	range of results (km) (\$/L)	
corn ethanol				
near-term corn ethanol	260	\$0.02	0 – 900	\$0 – \$0.05
EISA 2022 mandate	270	\$0.02	0 – 900	\$0 – \$0.05
large-scale cellulosics	430	\$0.02	0 – 1200	\$0 – \$0.05
cellulosic ethanol				
EISA 2022 mandate	170	\$0.01	20 – 1000	\$0 – \$0.04
large-scale cellulosics	330	\$0.02	10 – 1200	\$0 – \$0.05

^a All costs in 2005 dollars.

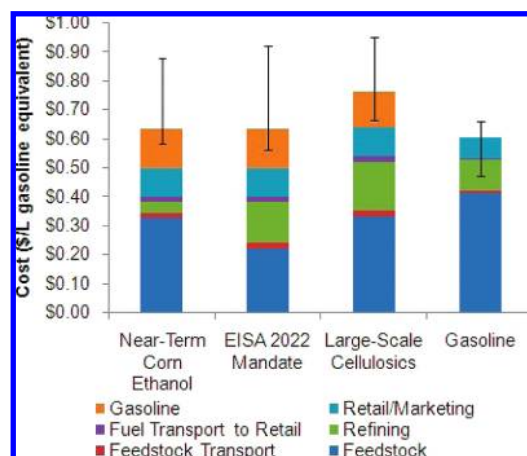


FIGURE 3. Cost components of delivered E85 for each scenario. E85 ranges indicate costs over all cities (MSAs); Average 2007 gasoline cost components from EIA (30, 31); Gasoline range is based on monthly average gasoline prices; The gasoline component of the E85 blend refers to the 15% gasoline in the E85 fuel blend; No subsidies or taxes are included in the cost estimates.

Estimated average ethanol distribution requirements for each scenario are shown in Table 2. There is a much larger percentage of rail transport in the *Large-Scale Cellulosics* scenario as a result of increased distribution distances. Corn ethanol distribution is similar for the *Near-Term Corn* and *EISA 2022 Mandate* scenarios, indicating that cellulosic ethanol is used to satisfy demand at MSAs not receiving ethanol in the *EISA 2022 Mandate* scenario. Effects of the disparity between primary supply and demand locations are seen in the *Large-Scale Cellulosics* scenario results. In this case, corn ethanol must be distributed 60% farther, on average, to reach available markets; cellulosic ethanol must be transported 95% farther.

The primary differences in estimated average delivered fuel costs can be seen in Figure 3. The bars indicate the range of E85 prices over all MSAs. The increase in ethanol production from 57 billion liters in the *Near-Term Corn Ethanol* scenario to 136 billion liters in the *EISA 2022 Mandate* scenario does not result in an increase in ethanol costs. This is primarily due to lower distribution costs for cellulosic ethanol and the fact that it is produced in the southeast, supplying different markets. As switchgrass production increases for the *Large-Scale Cellulosics* scenario, the spatial concentration of cellulosic ethanol production increases, thus larger transport distances are required to reach a sufficient market. In all scenarios, there is a 2-fold variation among

delivered ethanol costs. Gasoline costs were calculated based on average retail price components in 2007 (30, 31). Recent high petroleum prices can be seen in Figure 3, where feedstock accounts for 68% of the total gasoline cost, compared to 35–50% for the E85 scenarios. Refining costs in the two scenarios with cellulosic ethanol production are three times greater than those for the *Near-Term Corn Ethanol* scenario, but comprise the same proportion of the total cost relative to gasoline, 20%. Pipeline distribution of ethanol has the potential for distribution cost reductions. However a significant amount of capital investment, on the order of \$200 000 to \$500 000 per km, would be required to build new pipelines (32) or to convert existing ones exclusively over to ethanol transport.

Greenhouse Gas Emission Implications of Ethanol Distribution.

The majority of GHG emissions from distribution (95%) are due to carbon dioxide from fuel combustion. Distribution of ethanol from the production facilities to the MSAs, whether by truck or rail, contributes the largest amount of emissions. Results indicate that emissions from ethanol distribution in the U.S. could be significant. The majority of LCAs for ethanol are focused on emissions from feedstock cultivation and ethanol production. GREET is used in several studies to estimate transportation distances and/or emissions factors (33–38). Some studies calculate regionally based distribution distances and use emission factors from GREET or similar models (39). Default assumptions for ethanol distribution modes in GREET version 1.8b include barge (40%), rail (40%), and truck (20%) transportation, with roughly the same typical travel distances as our model (40). Using modal share and transport distance assumptions, GREET calculates an emissions factor of 40 g CO₂/L ethanol. Results from this study indicate that, in an optimized model with full market penetration of E85, over 70% of the ethanol would be transported by truck, with an average distance of 110 km. Of the remaining 30%, very little would be expected to travel by barge due to the competition with rail. Despite the increase in the truck modal share, the emission factor calculated using modal shares and average distances from this study and GREET emissions is 17 g CO₂/L. However, there are several cities that receive ethanol transported 400 km by truck, with a GREET-based emissions factor of 68 g CO₂/L, emphasizing the importance of regional distribution.

Transportation emissions calculated in this study for a large-scale ethanol production and distribution system could have a significant impact on life cycle emissions. Average estimated transport emissions agree with those in previous studies; however, there is a large range of emissions, depending on transport distances. Additional transportation requirements for cellulosic ethanol feedstock, similar to those for corn, could result in a doubling of total life cycle emissions if rail is not utilized. Transportation distances and emissions presented in the literature are applicable for regional ethanol production and distribution. However, they are not appropriate for long distance ethanol and/or feedstock distribution requirements, which are representative of a more realistic, nonoptimal nationwide ethanol system. Detailed results appear in pages S15–S16 of the SI.

Impacts of Ethanol Transportation. Some guiding principles for increasing ethanol use and distribution in a cost-effective manner can be taken from this study. Feedstock and ethanol transport can be significant cost components for corn and cellulosic ethanol. Since the ethanol product is cheaper to transport than the biomass feedstock, refineries should be located closer to the feedstock source than the demand centers. Even following this general rule, ethanol distribution costs will be significant. This study assumes a significant portion of the ethanol will be transported by rail, which is already operating at or near capacity. Pipelines were not considered in this study, as specific data on location and

capacity are not publicly available. In contrast to rail lines, which are located throughout the U.S. and generally within five kilometers of each MSA, pipelines are not as ubiquitous. In a survey of 20 ethanol facilities in Iowa, all but one had rail access and the state government is subsidizing spurs to connect facilities to existing lines (29). An ethanol pipeline system would require an optimized combination of main and branch lines to minimize capital and operation costs. Furthermore, the relatively small production volume and large spatial distribution of many ethanol facilities, especially when compared to oil refinery production volumes, may not justify pipeline construction. Rather than producing ethanol from biomass, production of biofuels such as butanol might be able to use existing pipelines. These issues require further investigation, as two companies recently announced a proposal to assess the feasibility of an ethanol pipeline from the Midwest to the Northeast (41). In sum there is great uncertainty about the long-term viability of building new pipelines given all of these aspects.

The use of regional high-level ethanol blends, as opposed to a national low-level blend, reduces ethanol transport and requires lower turnover of the vehicle fleet. The current standard is that ethanol blends greater than 10% require the use of FFVs. However, initial studies investigating the effect of E20 use in conventional automobiles indicate that this higher blend may not have detrimental effects on vehicle fuel supply and engine parts (42–46). The *Large-Scale Cellulosics* scenario would require turnover of almost half of the light duty vehicle fleet, assuming these vehicles would run only on E85. FFV sales in the U.S. increased 20% per year from 2004 to 2007 (47). Sales must continue to rise between 14 and 18% per year in order to satisfy the FFV requirement for these scenarios (Table 1).

Results from the least-cost distribution scenarios in this study (pages S10–S16 in the SI) assume that all producers are acting in concert. The model results differ from current ethanol consumption patterns, which are strongly influenced by local and state-level regulations and policies and competitive market forces. Of the five states with the highest consumption as percent of fuel demand in 2005, four are located in the Midwest (48). The fifth state, Connecticut, replaced 8.5% of its petroleum demand in 2005 by consuming 610 million liters of ethanol. In the three ethanol production and distribution scenarios analyzed in this study, none of the MSAs in Connecticut receive ethanol. California is the highest ethanol consumer, responsible for 23% of ethanol consumption in 2005 (3.5 billion liters). This provides a staggering comparison to the estimated least-cost distribution from the *Large-Scale Cellulosics* scenario, where only one-third of one percent of the 270 billion liters of ethanol produced was allocated to MSAs in California. California did not receive any out-of-state ethanol in any of the scenarios, indicating that costs and distribution requirements for the modeled scenarios would increase drastically if California and other coastal states increase their consumption of ethanol produced in the Midwest.

This analysis assumes that ethanol will be produced and distributed in an optimized system designed to minimize costs. The actual system will likely have both higher costs and emissions, particularly if transport congestion is considered. Many factors could influence production and end market locations, including state and local government incentives and mandates. The analysis emphasizes the importance of regional alternative fuel strategies. Ethanol should be pursued in areas near feedstock production, while different transportation fuel alternatives, such as plug-in hybrids, should be explored in other areas remote from feedstock sources.

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Supporting Information Available

Detailed information on the ethanol cost model construction and assumptions can be found in the Supporting Information. This information is available free of charge via the Internet at <http://pubs.acs.org>.

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