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A National Laboratory Market and Technology Assessment of the 30x30 Scenario

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Technical Report
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Foreword
To achieve the goals of the President's Advanced Energy Initiative DOE-OBP set a goal of 30x30 (Supply 30% of 2004 motor gasoline demand with biofuels by 2030). To set a research agenda towards accomplishing the 30x30 goal three efforts were initiated. Firstly, a workshop was held on August 1 and 2, 2006 where industrial, academia, and governmental biomass experts were assembled to discuss and develop a plan for achieving the 30x30 goal (OBP 2006). Secondly, the National Laboratories were charged with performing a market drivers and technology needs assessment of the 30x30 scenario, which is this document. Finally a posture plan was developed by OBP in conjunction with the other appropriate agencies and departments to coordinate an R&D plan for achieving the 30x30 goal. Together these three documents set the plan for achieving the 30x30 goal.

Executive Summary

Ethanol production from both corn and cellulosic feedstocks shows considerable promise to help lessen demand for imported oil as well as increase domestic energy security. However, we need to address the question: "What is an appropriate volume goal for ethanol production and in what timeframe?" Then given this goal, what do we need to accomplish in terms of in R&D, deployment, and market investment to achieve this goal?

After much discussion and analysis, the U.S. Department of Energy (DOE) selected the goal of supplying 30% of the 2004 motor gasoline demand with ethanol by the year 2030. This roughly translates to producing 60 billion gallons of ethanol per year on a Btu-adjusted basis by 2030—the 30x30 goal. This goal was selected because it represents an aggressive target that translates into a significant positive national impact but is well within the maximum potential for ethanol. A timeframe of 24 years from the present is considered aggressive but not short enough to be overly disruptive to market change dynamics.

This scenario report describes the market drivers and technology requirements and presents a plan for achieving the 30x30 goal with ethanol produced from both starch and cellulosic feedstocks, and outlines a scenario that is realistically achievable with sustained, integrated effort by government, academia, and the private sector. Since the 30x30 goal is in essence a market goal, this report describes a market driven approach for achieving the 30x30 goal.

Meeting the 30x30 goal calls for strategies that reduce biomass feedstock cost, technology risk, and ethanol price during the early years of industry adoption of lignocellulosic biomass technology as corn ethanol production is reaching its peak. Investor attitudes toward new technology raise the risk of building the first full-scale commercial plant to a higher level. Investors wait until market value for fuel raises enough to overcome their risk-aversion.

Design studies and the associated production costs are tied to specific years to account for inflation effects on operating and capital costs. The studies from the national labs are typically aligned with petroleum cost studies from the Energy Information Administration (EIA). These costs can be updated using inflation factors if the original cost calculations are available. For example, the Aden et al. (2002) biochemical design report calculations were originally done for 2000 dollars, and subsequently updated to 2002 dollars. The Phillips et al. (2007) thermochemical design report calculations are done in 2002 dollar. Hence for consistency purposes all dollar targets in this report are presented in 2002 dollars.

Ethanol can have major effects on the fuel supply for transportation in the United States—especially by 2050. However, scenarios for meeting the 2030 goal associated with the 30x30 initiative call for aggressive government policy and the ability to build on past decades of research on cellulosic ethanol technology. The scenario that achieves the 30x30 scenario is one in which prices prevail, initial incentive payments of $20/dry ton are made to farmers, and a relatively brief extension of the federal incentive for ethanol is enacted.

The technology targets of the 30x30 initiative for 2012 and 2030 are not, by themselves, sufficient to create a 60-billion-gallon/year ethanol industry by 2030. Meeting the 30x30 goal—even under a high oil price forecast—calls for a combination of strategies to reduce biomass feedstock cost, conversion cost, technology risk, and ethanol price during the early years of industry adoption of lignocellulosic biomass technology, once corn ethanol production has reached its peak.

An important strategy for speeding up technology adoption is to rely on past and ongoing DOE industrial partnerships to deploy first-generation technology that may be ready before the program meets its 2012 target of $1.07/gallon ethanol. To look at the effect of such a strategy in the BSM, we assumed that some form of first-generation technology is 80% complete in terms of R&D up to the pilot scale and that this technology would lead to ethanol at a nominal production price of $1.30/gallon. With this jump-start on technology development and the assumption of high oil prices, investors begin demonstration work much earlier.

Supplementing this strategy with two other policy levers leads to achievement of 60 billion gallons/year. These policies include extending the existing ethanol subsidy by five years to 2015 and providing payments to lignocellulosic biomass suppliers for residues and energy crops. A payment of $20/dry ton of biomass is equivalent to paying producers $40/ton of carbon dioxide recycled in the ethanol fuel life cycle.

The modeled scenario for achieving the 30x30 goal builds as follows:

- Prior to the President's Advanced Energy Initiative (Pre-Initiative) which had the $1.07/gallon cellulosic ethanol production target set for 2020, only corn ethanol is deployed to the maximum potential of ~16 billion gallons. Cellulosic ethanol does not achieve deployment under this scenario due to the fact that it never overcomes the risk hurdle for investors.

- In the first step, achieving the $1.07/gallon target is accelerated to 2012. Research indicates that this action has essentially no effect on ethanol deployment since cellulosic ethanol fails to clear the risk hurdle. Therefore under this scenario only starch-based ethanol is deployed up to the maximum potential of ~ 16 billion gallons.

- In the second step, adding the 1st generation technology incentive provides for a government cost share of 50% for initial demonstration-scale facilities and 40% for initial full-scale facilities. In this case ~25 billion gallons of cellulosic ethanol capacity are deployed by 2030. Combined with a starch-based ethanol capacity of ~13 billion gallons, this equals a total ethanol deployment of ~ 38 billion gallons of ethanol by 2030. Although this amount is significant, it fails to achieve the 30x30 goal.

- In the third step, adding a policy incentive of a payment for biomass to the grower of $20/dry ton through 2020 increases cellulosic ethanol deployed capacity to over 44 billion gallons by 2030, and when combined with the 2030 starch-based ethanol deployed capacity of 11.2 billion gallons, total ethanol capacity reaches ~55 billion gallons. Although this is close the 30x30 goal, the goal is still not achieved.

- Finally, in the fourth step, by extending the current ethanol subsidy of a fixed \$0.51/gallon of ethanol by 5 years (to 2015), ethanol production and use reaches ~ 60 billion gallons/year.

Adding the additional policy incentives essentially accelerates cellulosic ethanol deployment in the marketplace by three to four years. This acceleration of cellulosic ethanol capacity has a significant impact in the total amount of deployed ethanol capacity by 2030. Although this data is not presented in this report, when our model was run out to 2050 all scenarios essentially predicted the same amount of deployed ethanol capacity, hence the model predicts that the primary affects of the grower payment and ethanol subsidy policy incentives is to accelerate cellulosic ethanol capacity into the marketplace and will have minimal impact on total ethanol capacity in the long-term.

To fully address energy and environmental effects of the 30x30 scenario, we also conducted a life cycle analysis for several ethanol production options. The analyses included all major activities associated with the production and distribution of biomass feedstocks and ethanol and the use of ethanol in motor vehicles.

To compare ethanol's relative energy and emission merits, life-cycle analysis of petroleum gasoline was also included. Thus, we analyzed five life-cycle cases:

1. Petroleum gasoline (the baseline fuel)
2. Corn to ethanol
3. Corn stover (representative of agricultural residues) to ethanol through the biochemical conversion process
4. Switchgrass to ethanol through the biochemical conversion process
5. Forest residues to ethanol through the thermochemical conversion process

Central to the success of the 30x30 goal is the availability of biomass resources and the efficiency with which these resources can be converted into transportation fuels. Aligning these components to replace 30% of 2004 motor gasoline demand by 2030 will require, among all else, process and technology flexibility.

The feedstock resource assessment in the "Billion Ton" study (Perlack et al. 2005) validates the feasibility of achieving the 30x30 goal, provided R&D efforts overcome technical barriers to the development of economically viable biomass conversion technologies. The feedstock resource base, however, includes a variety of regionally specific biomass materials with a range of chemical and physical properties.

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1. Introduction

Ethanol production from both corn and cellulosic feedstocks shows considerable promise to help lessen demand for imported oil as well as increase domestic energy security. However, we need to address the question: "What is an appropriate volume goal for ethanol production and in what timeframe?" Then given this goal, what do we need to accomplish in terms of in research and development (R&D), deployment, and market investment to achieve this goal?

After much discussion and analysis, the U.S. Department of Energy (DOE) selected the goal of supplying 30% of the 2004 motor gasoline demand with ethanol by the year 2030. This roughly translates to producing 60 billion gallons of ethanol per year on a Btu-adjusted basis by 2030, herein after referred to as the 30x30 goal. This goal was selected because it represents an aggressive target that translates into a significant positive national impact but is well within the maximum potential for ethanol. A timeframe of 24 years from the present is considered aggressive but not short enough to be overly disruptive to market change dynamics.

This scenario report describes the market drivers and technology requirements and presents a plan for achieving the 30x30 goal with ethanol produced from both starch and cellulosic feedstocks, and outlines a scenario that is realistically achievable with sustained, integrated effort by government, academia, and the private sector. Since the 30x30 goal is in essence a market goal, this report describes technology needs and a market driven approach for achieving the 30x30 goal.

1.1 President's Advanced Energy Initiative – Changing the Way We Fuel our Vehicles

President Bush succinctly stated in his 2006 State of the Union Address: "America is addicted to oil." In 2004, the United States used almost 21 million barrels of crude oil per day; approximately 58% of this total was supplied by imports. The transportation sector, which relies almost entirely on petroleum products, accounts for two-thirds of U.S. petroleum use. Gasoline is the dominant transportation fuel in the United States, with a 2004 consumption of approximately 140 billion gallons. The Energy Information Administration (EIA) predicts that expected increases in total miles traveled will outweigh all vehicle efficiency improvements and lead to a one-third increase in gasoline consumption that can only be met by imported crude oil. In this scenario, EIA predicts that imports will account for 62.5% of total domestic oil use by 2030.

In order to reduce the Nation's future demand for oil, President Bush proposed the Advanced Energy Initiative (White House, January 2006) which outlines significant new investments and policies to (1) change the way we fuel our vehicles and, (2) change the way we power our homes and businesses. Together, these efforts will help the United States reach the President's long-term goal of reducing our oil imports from the Middle East by 75% by 2025 (Bush, State of the Union Address, January 31, 2006).

Currently, most ethanol is produced from grain; however cellulosic (biomass) ethanol has long been recognized as an important component of a sustainable ethanol marketplace. The

President's specific goal for biomass, as stated in the Advanced Energy Initiative, is “to foster the breakthrough technologies needed make cellulosic ethanol cost-competitive with corn-based ethanol by 2012” (White House, 2006). Reducing the cost of cellulosic ethanol will be a major step in enabling greater use of this alternative fuel to help reduce future U.S. oil consumption and is a critical component of “changing the way we fuel our vehicles.”

Although biomass has long been recognized as the only domestic, sustainable, and renewable primary energy resource that can provide liquid transportation fuels, long-standing questions regarding the domestic biomass supply have been:

- What is the production potential of cellulosic ethanol, and
- Can it have a significant impact on imported oil displacement and long-term energy security?

In response to these questions, an in-depth study, “Biomass as Feedstock for a Bioenergy and Bioproduct Industry: the Technical Feasibility of a Billion-Ton Annual Supply” (Perlack et al., 2005) was performed, herein after referred to as the Billion Ton Study. This study estimated that the United States has the potential to produce up to 1.3 billion tons of biomass annually on a sustainable basis without impacting food, feed, or fiber uses. To put the ethanol production potential in perspective, almost 60% of 2004 motor gasoline demands on a Btu-adjusted basis could be met with ethanol from grain and biomass, or approximately 125 billion gallons of ethanol.

1.2 Basis for Ethanol

This scenario is for biomass only, with the primary driver being a policy for reduction in demand for imported oil. This scenario does not include linkages with other scenarios for imported oil displacement such as coal to liquids.

Ethanol is the biofuel selected for this scenario both because of its near-term availability and to simplify the analysis of the distribution and vehicle needs. Other key justifications for choosing ethanol include:

- There is a well-developed body of work addressing the use of ethanol as a transportation fuel; both in the near term as low volume percentage (E10) blending stock with gasoline (an octane enhancer and to meet the oxygen requirements for RFG-mandated areas) and at higher blends (E85) as the primary constituent of transportation fuels.
- Ethanol is recognized as a commodity fuel and has market acceptance.
- Grain-based ethanol has already created market acceptance with well documented fuel properties and emission profiles.
- Flexible fuel vehicle (FFV) technology exists, is in the marketplace, and is growing.
- Many life cycle analysis (LCA) studies and energy balance studies have been performed on both starch and cellulosic ethanol so the environmental and energy profiles are well known.
- Wet and dry mill grain-based ethanol production is a mature commercial technology with well proven economics.

- Cellulosic ethanol conversion technology, although not yet a commercially viable technology, has received considerable development in the laboratory and R&D pathways exist to develop the technology to the market target production cost of $1.07 gallon (Foust et al., 2006).

However, a major barrier towards achieving the 30x30 goal is developing and deploying the necessary distribution and end use infrastructure (Section 5). Although there is an ethanol distribution and use infrastructure in place to distribute existing grain ethanol production (~ 5 billion gallons/year), it is highly unlikely that this infrastructure can be simply extended to accommodate the 60 billion gallons/year required to meet the 30x30 goal. Therefore distribution infrastructure is included as a critical component of realizing the 30x30 goal.

1.2.1 Ethanol Caveat

An important caveat is that this analysis presents a scenario to meet the 30x30 goal with ethanol. Clearly ethanol is not the only biofuel that can be produced; Fischer-Tropsch liquids, di-methyl ether (DME), methanol from biomass gasification, and butanol from alternative fermentation processes are just a few examples of other biofuels that could be produced. As in any scenario, forecasting is not absolute and exclusive in that other equally credible scenarios could be developed using other biofuels choices, feedstocks, and conversion technologies. Ultimately, market factors will dictate how the biofuels industry develops. Readers should not misinterpret this scenario as stating nor claiming that ethanol is the only viable biofuel option, but simply that a credible argument can be made for ethanol deployment at 30% of motor gasoline given favorable market drivers and reasonable assumptions.

1.3 Basis for Choosing Ethanol Production Technology Routes

Because of the wide diversity of biomass feedstocks, conversion technologies, integration scenarios, and potential products, a multitude of biorefinery options are possible. Even limiting the 30x30 scenario to the production of ethanol gives us many options to consider regarding the selection of specific feedstocks and conversion technologies. To help sort out all the possibilities, guide the research efforts, and identify the key interfaces that will enable the establishment of commercially-viable integrated biorefineries, the Office of the Biomass Program (OBP) has identified seven primary technology pathways (OBP Multi-Year Program Plan [MYPP], 2006). These pathways are linked to the resource base identified in the Billion Ton Study, the existing segments of today's bio-industry where possible, and future bio-industry market segments where envisioned. The pathways are focused on feedstock production, feedstock logistics, and ethanol production elements of the supply chain. The details of each pathway are described in the OBP MYPP. Each pathway represents a generic set of potential biorefinery scenarios for a specific biomass resource base, as shown in Figure 1-1. The oil seed pathway is not considered in this 30x30 scenario because of the focus on ethanol.

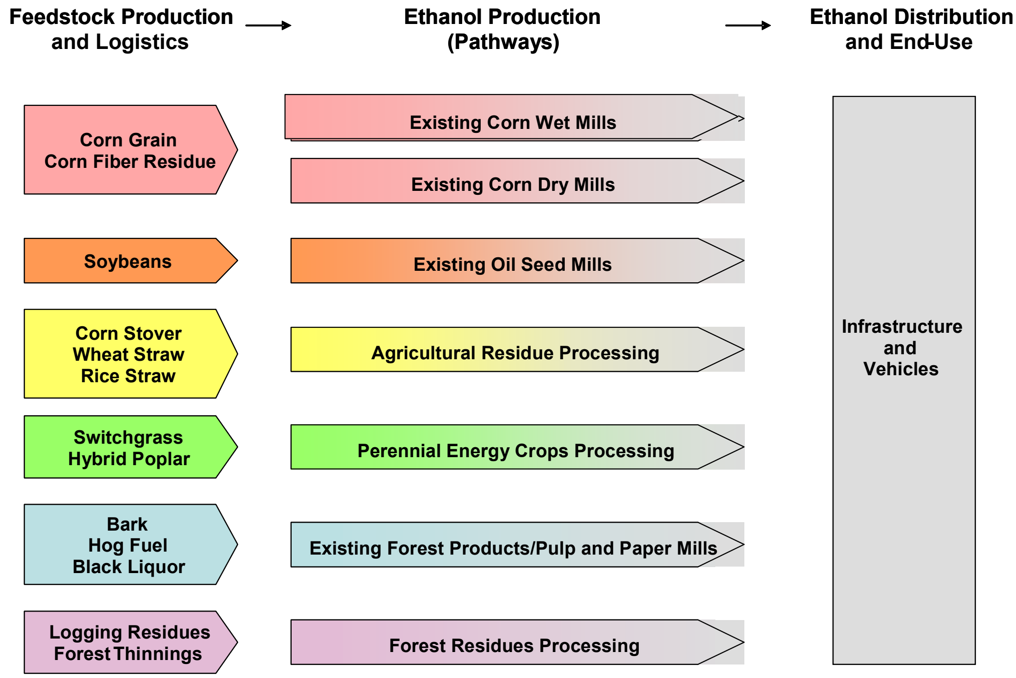

Figure 1-1. Resource-based Conversion Pathways

From the diverse range of feedstocks outlined in the Billion Ton Study, we have selected four feedstock into ethanol conversion technology options to analyze in this scenario.

1. Existing corn wet and dry mill technology for continued deployment of corn grain based ethanol. Since this is already a vibrant commercial technology, the 30x30 scenario does not require additional development of this technology.
2. Biochemical conversion (Section 4.2.1) of cellulosic feedstocks to ethanol.
3. Thermochemical conversion (Section 4.2.2) of cellulosic feedstocks to ethanol.
4. Advanced state of technology conversion (Section 4.2.3) incorporating both advanced biochemical and thermochemical aspects at larger scales.

1.4 Technology Targets as They Relate to Production Cost Targets

1.4.1 The 2012 Technical Target

As stated earlier, the Advanced Energy Initiative defines the technology goal for cellulosic ethanol as "to foster the breakthrough technologies needed to make cellulosic ethanol cost-competitive with corn-based ethanol by 2012." Although this is a quantifiable technology target in the context of the 30x30 goal, it needs to be considered in the larger sense to determine if it is sufficient to enable large-scale market penetration of cellulosic ethanol at a level where it can directly compete with gasoline as a motor fuel.

The $1.07 per gallon production cost for cellulosic ethanol has been defined as competitive with corn-ethanol. At this cost, cellulosic ethanol production would be low enough for entry into the existing ethanol market. The value can be put in context with the historic ethanol price data as shown in Figure 1-2. The $1.07 per gallon value represents the low side of the historical fuel ethanol prices and hence given historical price data, cellulosic ethanol would be commercially viable at this cost of production.

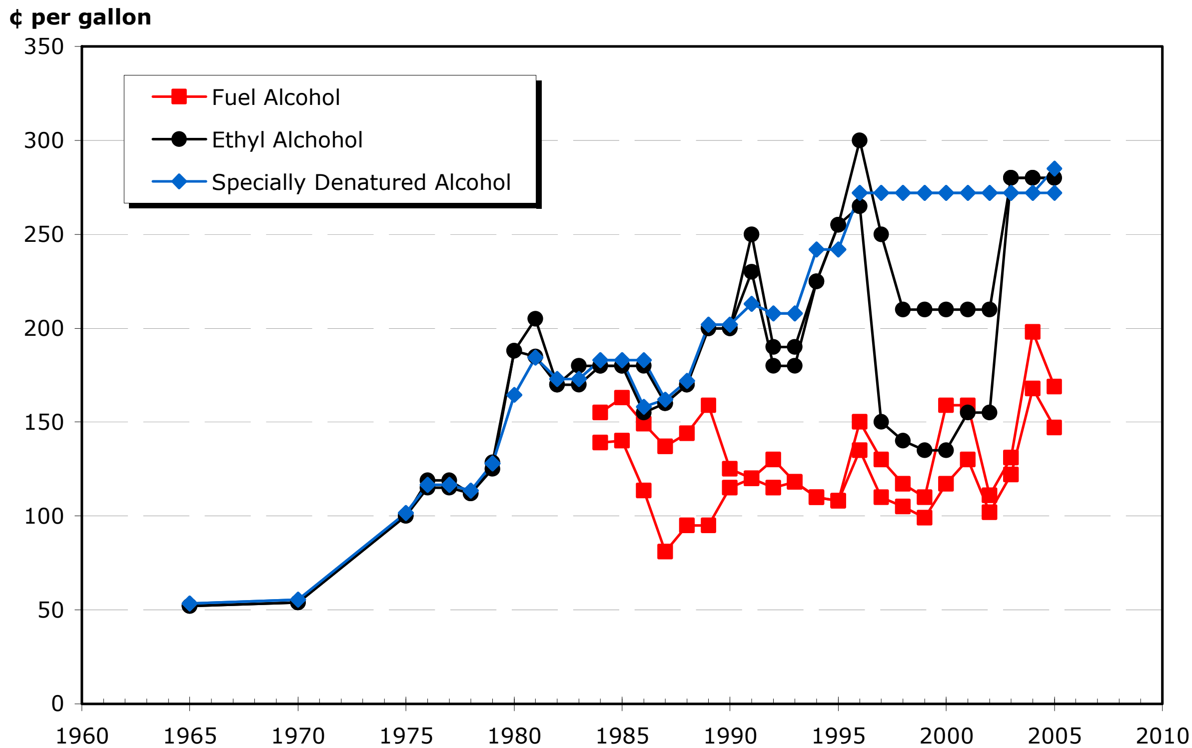

Figure 1-2. U.S. List Prices for Ethanol

In addition, the $1.07 per gallon of ethanol price target is also in-line with current gasoline rack or pre-tax, prices. To compare the target ethanol price with the price of gasoline on an "apples to apples" basis at the pump, the ethanol price must be adjusted as follows:

1) Adjust the ethanol price from dollars per gallon of ethanol to dollars per gallon of gasoline equivalent by correcting for the two-thirds lower energy content of ethanol compared to gasoline. This increases the $1.07 to $1.62 per gallon of gasoline equivalent.

2) Adjust ethanol price from plant gate to retail price. The price of gasoline includes, on average, $0.40 per gallon for taxes and $0.23 for distribution. Assuming the same costs for ethanol gives it a retail price slightly higher than that of gasoline when oil is at $55 per barrel, as shown in Figure 1-3. This price at pump analysis does not assume any subsidy for ethanol.

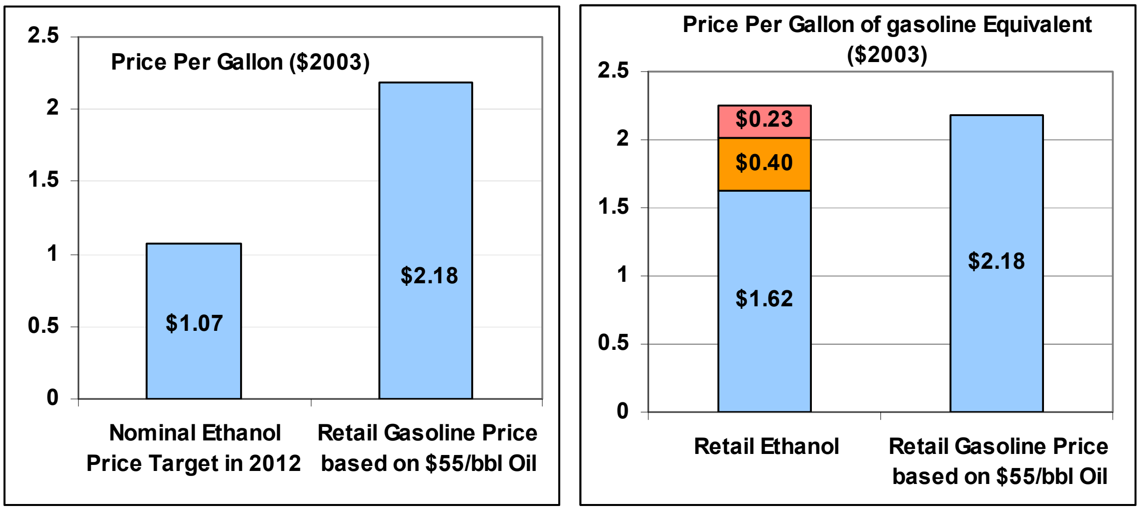

Figure 1-3. Ethanol and Gasoline Price Comparison

In 2002, the National Renewable Energy Laboratory (NREL) published a detailed technology assessment (Aden et al., 2002) that outlines the technology basis for the $1.07 market target case via a biochemical conversion pathway. The $1.07 market target includes feedstock production, feedstock logistics, and conversion cost components. Imbedded in this market target are the assumptions discussed in Table 1-1.

Table 1-1. Economic Assumptions Used in all Calculations

Nth plant" cost and performance based on pilot plant scale (2 to 5 tons per day of biomass) data
A minimum selling price based on a 10% rate of return on investment (ROI)
A minimum selling price that is ***not*** based on availability of tax incentive
A biomass feedstock cost of $35 per dry ton at the throat of the pretreatment reactor
A minimum selling price at the plant gate (exclusive of fuel distribution costs, marketing costs, and taxes).

Sections 4.2.1 and 4.2.2 outline the research pathways towards achieving the $1.07 market target via biochemical and thermochemical conversion routes. However, the goal of $1.07/gallon in 2012 is not sufficient in of itself to achieve the 30x30 goal even given DOE's EIA crude oil high price projections out to 2030. Market analysis (Section 2) shows that, if the goal of a production price of $1.07/gallon is the ultimate endpoint for the technology, the 30x30 goal will not be achieved. Hence a second technology target is used to meet the goal.

1.4.2 The 2030 Technical Target

An advanced state of technology target with a 70% reduction in conversion cost from the $1.07 case by 2030 is used to meet the 2030 goal. This target is needed because:

1. Feedstock costs will probably not remain constant at $35/ton. As the biorefinery industry matures, feedstock prices will likely increase (as is the case for most

commodity feedstocks). The price increase will be driven by the use of higher-cost biomass and natural market dynamics. Analysis indicates that grower payments could reach up to $50/[1]ton (Section 4.2.3) to capture all the cellulosic feedstocks necessary to achieve the 30x30 goal.

2. To drive the necessary growth of the ethanol industry, the delta between production price and selling price must be sufficient to drive maximum capital investment. Section 4.2.3 outlines the advanced state of technology research pathways that will be required to achieve this target.

The advanced technology case attempts to reduce the conversion cost component of the ethanol production cost to accommodate these concerns as well as take advantage of economies of scale advancements that naturally come with a more mature industry. Table 1-2 outlines aspects of the advanced conversion target.

Table 1-2. Advanced Technology Conversion Targets

Case	**Year**	**Plant Size**	**Operating Costs**	**Feedstock Contribution**	**Minimum Ethanol Selling Price (MESP)**
		(tonnes/day)	**($/gallon)**	**(S/gal) & ($/bdt)**	**(S/gallon)**
$1.07/Gallon Market Target	2012	2,000 2,185 dry tons/day	$0.68	$0.39/gal -- $35/bdt	$1.07
Advanced Technology	2030	2,000	$0.49	$0.76[1]/gal -- $71/bdt	$1.25
Advanced Technology	2030	10,000[2] 11,025 dry tons/day	$0.21	$0.76[1]/gal -- $71/bdt	$0.97
Cost Reduction in Conversion Technology Because of Advanced Technology			$0.19		
Cost Reduction in Conversion Technology Because of Economies of Scale			$0.28		

[1]Estimated 2030 feedstock cost based on larger grower payments to capture all cellulosic feedstocks (see Section 4.2.3.1).
[2] This plant size is specified here purely to show relative cost impacts of economies of scale versus advanced technologies. Realistically feedstock logistics would limit plant size below this level.

However, as the market assessment will show in Section 2, the proposed targets for ethanol technology improvement are not, by themselves, sufficient to push the ethanol industry to the 30x30 goal—even with higher oil prices. Hence, in addition to technology cost targets, market and policy incentives will be required to achieve the 30x30 goal.

1.5 *Achieving The 30x30 Goal: A Market Driven Approach*

Meeting the 30x30 goal calls for strategies that reduce biomass feedstock cost, technology risk, and ethanol price during the early years of industry adoption of lignocellulosic biomass technology as corn ethanol production is reaching its peak. Investor attitudes toward new

[1] All “ton” references in this report are “dry”

technology raise the risk of building the first full-scale commercial plant to a higher level. Investors wait until market value for fuel raises enough to overcome their risk-aversion.

The market analysis presented in this scenario makes use of a newly developed "system dynamics" model that can be used to understand the timing ("dynamic") implications of hypotheses about how the players in the marketplace behave and how they will respond to new technology developments. That model—the Biomass Scenario Model (BSM) (Appendix B) — has served as a useful prototype for the modeling that will be needed to strategically assess R&D and deployment strategies. Given assumptions about the behavior of farmers and investors and about the future state of agricultural, energy and crude oil, and vehicle markets, we used the BSM to identify scenarios under which the 30x30 goal can be met. Thus, these results are hypotheses and not forecasts. Furthermore, the scenarios sketched out in this report do not represent the *only* possible strategies.

There are two sets of drivers in the BSM that can be used to determine the success of the scenario technology goals as they relate to production cost targets, and policy and market incentives to make ethanol more competitive in the marketplace. The scenario presented here uses the best mix of these tools to achieve the 30x30 goal. The scenario for achieving the 30x30 goal is based on achieving the cost and technology targets goals stated below.

1. Continue the successful deployment of corn-based ethanol up to its maximum potential (9.3 – 17.2 billion gallons/year).

2. Develop and demonstrate at the pilot scale both biochemical and thermochemical cellulosic ethanol conversion technology at the $1.07[2] market target by 2012.

3. Develop and demonstrate at the pilot scale advanced cellulosic ethanol conversion technology that significantly reduces the conversion cost component from 64% of the total ethanol production cost in the $1.07 case to 22% of the total ethanol production cost by 2030.

4. Provide two market incentives to accelerate the deployment of ethanol.
    a. Continue the current $0.51/gallon ethanol tax incentive till 2020.
    b. Provide a $20/ton subsidy for cellulosic feedstocks until 2025.

5. Develop the necessary distribution and vehicle infrastructure to support the 30x30 goal.

6. Compare with EIA Annual Energy Outlook (AEO) high oil price projections[3]

Applying the assumptions listed above to the BSM produces the ethanol production profile shown in Figure 1-4.

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[2] The $1.07 per gallon of ethanol market target price is calculated using year 2002 dollars.
[3] (http://www.eia.doe.gov/oiaf/analysispaper/biomass.html 7/2002)

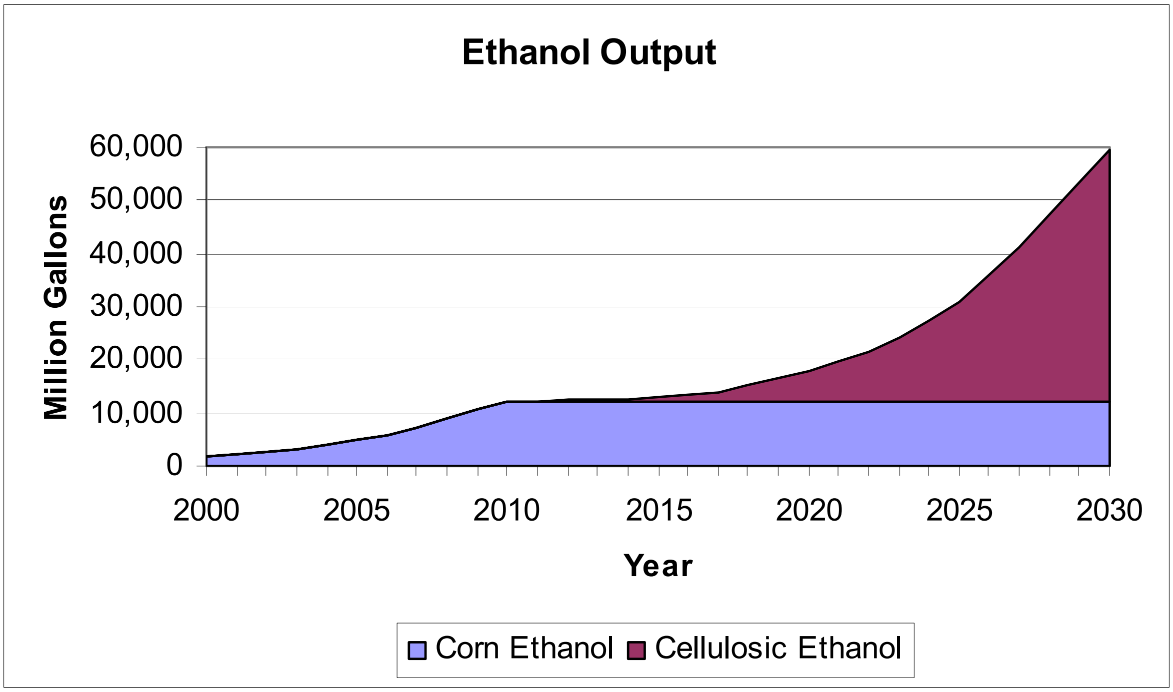


Figure 1-4. Ethanol Production Profile for the 30x30 Market Target

The market analysis shows that extending the ethanol subsidy beyond 2020 has no added benefit if progress in R&D continues and is successful in reducing the conversion cost of ethanol to the targets shown in Table 1-2. The same holds true for the biomass feedstock payments. Hence, achieving the Table 1-2 targets by 2030 is critical to allowing these market incentives to sunset. The analysis also shows if research does not progress towards achieving the 2030 target, extending the ethanol subsidy until 2030 or until the advanced state of technology target is achieved provides additional robustness towards achieving the 30x30 goal, but at a far greater cost.

1.5.1 Deployment

A critical aspect of achieving the 30x30 goal is deployment of all the aspects of the ethanol supply chain from feedstock production to end use vehicle technology. As outlined in Section 2, a market driven approach will be used to develop this scenario. We assume that market factors will drive the deployment of ethanol and the types of ethanol production technologies deployed.

This scenario relies on the development of two cellulosic ethanol conversion technologies, a biochemical and a thermochemical option. This two-tiered approach to cellulosic ethanol technology development provides robustness and near term options; with technology opportunities for improved yields and improved economics in the long-term by integrating the two options.

Attempts are not made in this scenario to crosswalk feedstocks with production technologies and industrial sectors. Geographic and market factors will dictate feedstock and conversion technology options and the assumption of this scenario is that industry will choose the combinations that provide the best economics for their particular set of conditions.

1.5.2 Fuel Distribution Infrastructure and the End User

The amount of ethanol required to meet the 30x30 goal far exceeds current production levels. Current infrastructure pathways are already close to capacity and researchers need to address the factors that will drive distribution infrastructure development. Currently, the BSM does not have a robust fuel distribution infrastructure market dynamics module; the BSM assumes that there will always be ample distribution pathways to accommodate the volume of fuel production. Section 5 provides additional analysis to determine the factors that will be necessary to drive the development of the distribution infrastructure to achieve these volumes and beyond. The BSM does have a vehicle end-use demand function that is based on future fleet assumptions.

1.5.3 Investors and Risk

Meeting the 30x30 goal will require that the financial and industrial communities invest close to $100 billion to construct new ethanol-production facilities. If, as detailed in this report, technology is developed such that production cost targets are met and the cost of competing petroleum products goes as projected in the EIA AEO (2006), there will be sufficient monetary return to support this level of investment. The challenge will not be in the long term, but will be in building the first or “pioneer” plants that prove the technology by taking higher risks and solving the real problems of the new technology.

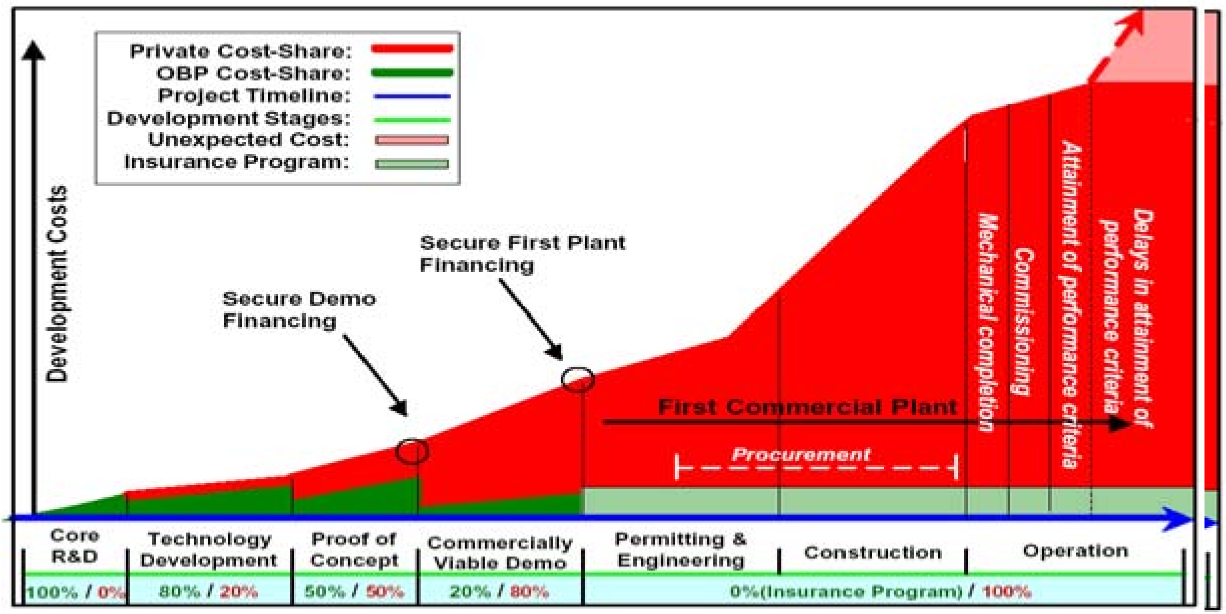
Merrow studied cost growth in the synfuels industry and found that it was not uncommon to drastically underestimate the costs associated with building production facilities based on new technology (Merrow et al., 1981). The synfuels industry was very similar to the now emerging biomass industry, where new process designs consisted of many new operations, including solids handling, and the product was a low margin, commodity fuel. To overcome these apparently inherent technology development hurdles, close attention to detail in the research, development, and demonstration phases is a must. Care must be taken to collect the appropriate data and scale-up a fully integrated process while making sure that all components are accurately accounted for in products, by-products, wastes, and recycles.

1.5.4 DOE’s Role in Risk Mitigation

A. Non Technical Areas of Risk

In an effort to identify non-technical barriers to cellulosic ethanol deployment, DOE held a forum (DOE 2004) of representatives from the private and public sectors. Participants included members of finance, policy, industry, and engineering organizations. DOE found that regulatory, policy, and market barriers are important, but the primary barrier is financial.

Figure 1-5 illustrates the magnitude of investment that must be made by industry and government to successfully commercialize a new technology. As shown in the figure, most investment is from industry. It should be noted that although construction costs can be predicted, unexpected costs incurred after the plant is built (e.g., process modifications to achieve design yields, rates, and operating costs) can be considerable and must be borne by operators and investors.



Source: DOE 2004.

Figure 1-5. Risk Framework

The DOE forum recommended five areas for continued federal assistance to overcome these non-technical barriers. The recommendations were:

1. Create a development primer.
2. Form a working group within government to help developers.
3. Help with off-take agreements (where possible).
4. Co-fund research and development.
5. Help with risk mitigation.

Table 1-3 summarizes how DOE will help in these areas.

Table 1-3. Deployment Assistance Recommendations

Recommendation	Reason	Approach
1. Project Development Primer	To overcome major logistical barriers of the deployment process	Outline a deployment primer on market analysis, permitting, applying for financing, and developing strategic partnerships.
2. Working Group	To expedite the permitting/ regulatory process	Coordinate with EPA and DOE to advise developers on how to streamline the process and minimize the effects of regional variation.
3. Off-Take Agreements	To increase financial backing (Banks prefer to finance projects that have secured a buyer of the final product.)	Identify and secure off-take agreements with local consumers as well as state, regional, and federal sources to secure markets for new technology.
4A. Current R&D Funding (20-80)	To help industry develop technology	Provide a 20-80 cost-share with industry for R&D efforts.
4B. Bench-/Pilot-Scale Testing (50-50)	To help developers prove technology functionality	Collaborate with industry to provide a 50/50 cost-share of small-scale testing of technology.
4C. Commercially Viable Demonstrations (80-20)	To help developers demonstrate technical and economic feasibility (Investors are unwilling or unable to provide high-risk capital for commercial plants.)	Provide 20%–30% cost-share for a large-scale demonstration plant to prove technical and economic feasibility.
5. Risk Mitigation	To allow corrective actions (when other options are exhausted) to ensure a successful commercial launch (Most projects fail because they have exhausted their capital prior to meeting performance guarantees.)	Establish a type of insurance program for commissioning and performance acceptance through the first year of operation, with review by independent engineers.

Source: DOE 2004

B. Technical Areas of Risk

Important activities for successful deployment include scale-up and demonstration of new technologies, followed by investment in full-scale facilities to offset the risks of cost overruns in pioneer plants.

DOE has sponsored research at several national laboratories and universities since the early 1980s to improve cellulosic biomass-to-ethanol conversion technology. Considerable progress has been made (Sheehan and Riley 2001a; Foust et al. 2006), and further cost reductions are being pursued.

In the past six years, DOE has increased its support of industrial projects. In 2004, two critical projects were completed that resulted in the world's largest enzyme producers reducing the cost of cellulose enzymes (which are critical to the conversion of cellulose to fermentable sugar) by more than 20 times. Two other ongoing cost-shared projects are with Abengoa Bioenergy and DuPont. These companies plan to conduct experiments with or leading to scaled-up integrated pilot plants. Abengoa's process will integrate cellulosic pretreatment with newly developed enzymes and a robust biocatalyst for the fermentation of biomass-derived sugars to ethanol (Abengoa 2003). Abengoa's pilot-plant phase will be completed in 2007. DuPont will conduct the laboratory work and engineering modeling and design necessary to scale-up to a pilot plant (DuPont 2003). This work will also be completed in 2007.

Activities that DOE is planning with industrial partners include a cost-shared, one-tenth-scale demonstration facility and a cost-shared commercial demonstration facility. These scale-up activities are critical to the successful long-term deployment of cellulosic ethanol conversion technology.

It assumed that DOE-led industrial projects will lead to scale-up technology that will satisfy the inflated return on investment required for pioneer plants prior to 2012. The initial plants will be augmented with cost-reduction technology developed by DOE through the pilot-plant scale. Once a sufficient number of plants have been established and optimized, the investment community will be comfortable with investments at lower, more conventional returns on investment. In a second scenario, DOE continues to reduce costs through 2012 at the pilot-plant scale. This will enable follow-on industrial cost-shared scale-up activities to ultimately build the pioneer plants. Following the same path as the first scenario, once a sufficient number of pioneer plants have been built and optimized, the investment community will consider this a mature technology with standard investment returns.

1.6 Achieving the 30x30 Goal

The significant increase in crude oil prices over the past two years and resulting high gasoline prices have renewed interest in biofuels and their potential. This report presents a detailed assessment of what is required to supply 30% of 2004 motor gasoline demand with ethanol by 2030.

A credible scenario for achieving the 30x30 goal with ethanol can be made, given AEO oil price projections (EIA, 2006). However, the scenario is extremely aggressive and can be achieved only with a focused and sustained government and private sector effort. To identify critical areas and the probability of success of meeting the goal, this document will be rigorously analyzed with a comprehensive risk assessment to validate the preferred approach to the 30x30 goal.

2.0 The Biofuels Industry

Most analyses performed to characterize the potential of biofuels technology are static. They are snapshots of the market and technology. But understanding deployment requires another dimension: time. Only in the context of time can we understand the sequence of events behind the deployment of biofuels technology.

Many software tools and techniques, with varying degrees of complexity and ease of use, are available for assessing and predicting dynamic behavior. The BSM (Appendix B) was created using a software tool known as STELLA, which provides a simple visual language for representing dynamic behavior in systems. Its relatively intuitive nature is well suited to the kind of general "what if" scenario building needed. The software allows users to evaluate interactions among supply chain components as they unfold over time, without the need for fluency in ordinary and partial differential equations.

2.1 The Biomass-to-Ethanol Supply Chain

2.1.1 The Supply Chain

The supply chain for biofuels production and use—from the farms to the vehicles—is shown in Figure 2-1.

Figure 2-1. The Biomass-to-Ethanol Supply Chain

Analytically characterizing all aspects of the supply chain in the scenario model would make it unwieldy. Instead, the model takes advantage of the spectrum of analytic descriptions offered by various (and individually more detailed) modeling activities. Indeed, the BSM has proved to be a valuable strategic modeling tool that pulls together results from other analytical efforts to construct a coherent "story" for the build-up of each component of the biofuels supply chain.

The model allows ethanol (from corn or lignocellulosic biomass) to compete with petroleum fuels in two markets: as a fuel additive (as an oxygenate, and/or an octane enhancer) and as bulk fuel supply (gasoline). The backdrop for these markets is the world oil market. The DOE EIA's AEO (Energy Information Administration 2006) provides projections for oil prices to 2030. The BSM incorporates a static picture of oil prices based on AEO 2006, which is extended to 2050 using linear extrapolation. The results presented here focus on the AEO 2006 "reference case" and the "high oil price case" (see Figure 2-2).

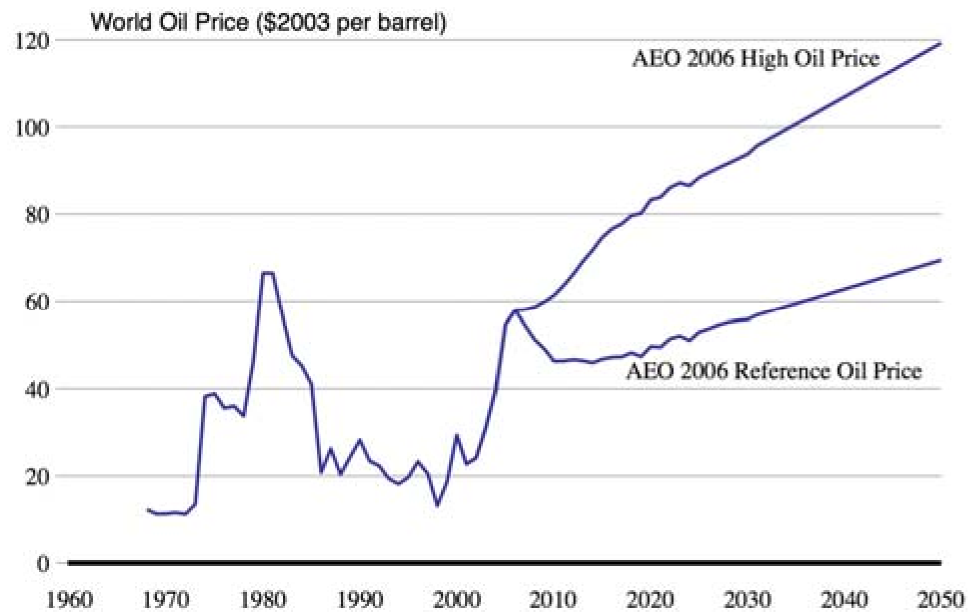


Figure 2-2. World Oil Price Scenarios

Oil prices are translated into gasoline prices using a linear regression of historical prices of oil and refinery gate gasoline prices (EIA 2005). If ethanol and gasoline compete solely on the basis of delivering energy to a vehicle, then gasoline prices can serve as a direct measure of the market competition that ethanol must beat. Analyses by ORNL were used to establish the added value of ethanol relative to gasoline in the fuel blend market (Hadder, 2000).

However, the BSM ignores the dynamics of building a fuel distribution system for E10 and E85. It is likely federal or state policies will be needed to ensure the timely introduction of an ethanol fuel infrastructure. This issue is addressed further in Section 5. The dynamics of building a fuel distribution system are dwarfed by the relative dynamics of developing, investing in, and building biomass conversion facilities.

Another possible barrier to high-volume market penetration of ethanol is the availability of ethanol-capable vehicles. The BSM includes a fleet vehicle turnover model that considers timing constraints on the introduction of E85 FFVs. The model contains two scenarios: (1) the business-as-usual introduction of FFVs combined with business-as-usual fleet average fuel economy and (2) an aggressive policy/technology-driven scenario proposed by the Union of Concerned Scientists (UCS) in which hybrid vehicle technology is combined with FFV technology to allow greater fuel efficiency and higher fleet capacity for E85 use.

The aggressive vehicle scenario is used in all results summarized in this section so as to not constrain the demand for ethanol. By not constraining the demand potential for ethanol, all of the areas in the biomass-to-ethanol supply chain can freely expand in the BSM. The business-as-usual vehicle scenario affects the ability to meet the 30x30 goal by retarding the demand.

However, since the UCS projections were chosen only to eliminate demand, we selected another model, VISION, to predict fleet growth for the 30x30 (Section 3).

The BSM includes four scales of technology: pilot (1–5 tons/day), demonstration (50 tons/day), pioneer (500 tons/day), and full (5,000 tons/day).

2.1.2 Key Actors

The BSM models the behavior of three key actors:

- Private sector investors
- [4]Farmers or growers
- Policymakers

Figure 2-3 shows schematically how these actors interact with one other and with the supply chain. The investor's response to the conditions of the fuel market, the feedstock supply market, and the state of the industry are the primary determinants of whether investments in ethanol (corn or cellulosic ethanol) production capacity occur. Investment in ethanol production capacity is, in turn, the primary determinant of the dynamics of ethanol production.

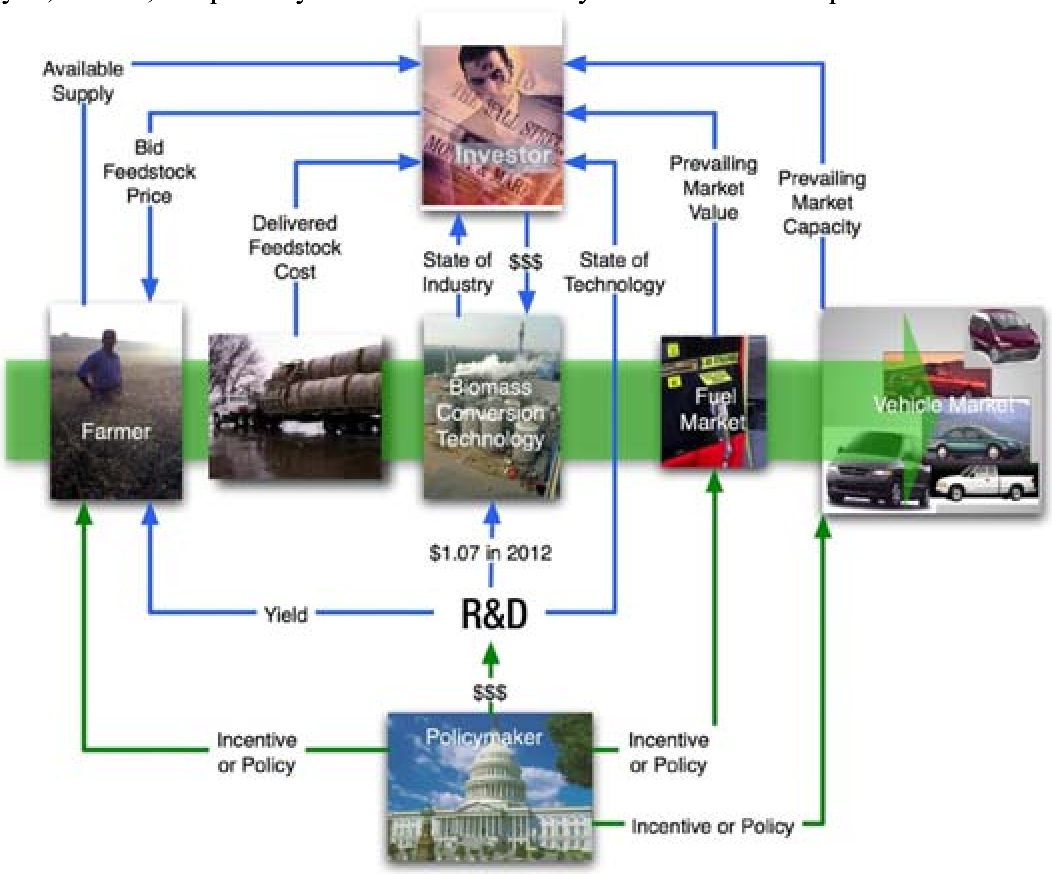


Figure 2-3. Dynamic Interactions among Investors, Farmers, and Policymakers in the Biomass Transition Model

[4] The term farmer, grower, producer, and landowner are used interchangeably throughout this report

Although it is a popular notion that the build-up of the supply chain for a new fuel such as cellulosic ethanol is driven by "market pull," Figure 2-3 illustrates that this is only partly correct. The investor must take into account market requirements for and constraints on the acceptance of ethanol as well as the requirements and constraints of the market controlling feedstock supply. Given these factors, the state of technology for converting biomass to ethanol is the remaining factor that can make or break investment in new ethanol production capacity.

2.1.2.1 Investor

The investor's calculation is relatively simple. The investor must consider:

- The cost of delivered (plant gate) biomass
- The capital and operating costs associated with converting that biomass into ethanol
- The prevailing market value of ethanol
- The market capacity for using ethanol

Working backward from the vehicle and fuel markets, the investor starts by seeing if the combination of E10 and E85 capacity in the vehicle fleet at a given point in time has room to absorb new ethanol production. If vehicle fleet demand is being met, the investor determines that the investment is not attractive, and no money is invested in new ethanol capacity. The investor also compares the minimum price of ethanol with the prevailing value for ethanol in the marketplace. As the ratio of prevailing market value to minimum ethanol selling price becomes greater, investment in new ethanol production capacity becomes more attractive—and money flows more rapidly into new ethanol projects.

It is important to understand how the investor establishes a minimum selling price for ethanol for a full-scale commercial facility. It is calculated by establishing:

- Total project investment (TPI) for the plant
- Non-feedstock operating costs for the plant
- Feedstock operating costs for the plant.

TPI and operating costs are based on the best available technology at a given time. The investor inflates the TPI to reflect cost growth if the project is a first-of-a-kind plant (Merrow 1981).

Lignocellulosic biomass feedstock costs are determined through a dynamic bidding process in which the investor in a new cellulosic ethanol plant looks at the available biomass inventory to determine if, at current prices, there is enough inventory to support a new processing facility. If not, the investor bids up the market price until the response from the biomass feedstock supply system is sufficient to meet demand. The BSM model shows that lags in the response of the feedstock supply market (e.g., because of the time required to establish a new stand of switchgrass) can lead to "commodity cycles" in which market price increases are followed by price collapse.

The investor will assign a risk factor that affects the required return on investment (ROI); the higher the risk, the higher the minimum ROI. This risk factor depends on perceived industry experience with the technology and the completed R&D and piloting. Thus, until cellulosic ethanol becomes established, investment in this technology is handicapped relative to corn ethanol technology because its risk-weighted cost of capital is higher.

2.1.2.2 Producer

The biomass producer's calculations are also relatively simple. The farmer (or grower) needs to answer the question: "Where is my best opportunity for generating income from my investment in farmland?" The farmer compares the potential revenue per acre for switchgrass (or for some other perennial energy crop) with the current revenue generated. If the ratio of potential revenue from switchgrass to revenue from existing crops is greater than one, then the farmer moves a percentage of land into switchgrass production. As the ratio increases, the rate of land turnover into switchgrass increases. The decision to supply biomass is "automatic." That is, the amount of biomass available is determined by the price offered by the biomass processor and is determined directly from fixed feedstock supply curves.

2.1.2.3 Policymaker

The BSM model makes no attempt to apply a logic or calculus to the decisions of the policymaker. Instead, it treats the response of policymakers as an adjustable input to the system. The policymaker has several levers available, depending on what "social good" is being considered. In the model, the policymaker can influence the economic calculi of the farmer and the investor in a number ways. For example, the policymaker can:

- Pay the farmer a credit for collecting, producing, and selling lignocellulosic biomass for fuels production
- Apply or modify fuel mandates (e.g., the Renewable Fuel Standard)
- Charge a carbon tax on all vehicle fuels based on carbon dioxide emissions (this is where life cycle analysis data characterizing gasoline, corn ethanol, and lignocellulosic ethanol are used)
- Extend the existing ethanol tax incentive
- Provide capital funding for first-of-a-kind technology investments at the commercial and demonstration scale.

Although all these options are available in the model, only options 1, 4, and 5 were necessary to achieve the 30x30 goal.

2.2 Possible Futures

All of the analyses presented here include the following assumptions:

- Private investment in demonstration-scale (50-ton/day) facilities occurs when the nominal price of ethanol reported from R&D meets the prevailing market value and facility operation shows a minimal (2%) ROI. (The BSM model downplays the role of ROI as a decision-making tool for the demonstration because the investor understands that the demonstration facility itself will not be a source of profit or return on capital.)

- Government funds are available for initial demonstration-scale facilities to cover 50% of total project investment.
- Government funds are available for the first full-scale demonstration facility to cover 40% of total project investment.
- Initial demonstration-scale cellulosic ethanol facilities will be built in existing corn ethanol facilities, which is predicted to reduce total project investment by 50% compared with a Greenfield project.
- Investors are willing to jump from demonstration scale (50 tons/day) to full commercial scale (5,000 tons/day).
- Financing is 40% debt and 60% equity, with debt financing available at 7.5%.
- Equity financing of a first-of-a-kind commercial facility requires a 30% ROI to account for technology risk. The ROI then declines to 10% after about the first 200 million gallons of production.
- Equity financing for corn ethanol facilities has a 10% ROI.
- There is aggressive adoption of FFVs.

2.2.1 Oil Price Scenarios

2.2.1.1 Meeting the 30x30 Goal in a High Oil Price World

The technology targets of the 30x30 initiative for 2012 and 2030 (see Section 1) are not, by themselves, sufficient to create a 60-billion-gallon/year ethanol industry by 2030. Meeting the 30x30 goal—even under a high oil price forecast—calls for a combination of strategies to reduce biomass feedstock cost, conversion cost, technology risk, and ethanol price during the early years of industry adoption of lignocellulosic biomass technology.

An important strategy for speeding up technology adoption is to rely on past and ongoing DOE industrial partnerships to deploy first-generation technology that may be ready before the program meets its 2012 target of $1.07/gallon ethanol (2002 dollars). To look at the effect of such a strategy in the BSM, we assumed that some form of first-generation technology is 80% complete in terms of R&D up to the pilot scale and that this technology would lead to ethanol at a nominal production price of $1.30/gallon. With this jump-start on technology development and the assumption of high oil prices, investors begin demonstration work much earlier.

Supplementing this strategy with two other policy levers allows us to produce 60 billion gallons/year (see Table 2-1) of cellulosic and grain ethanol. These policies include extending the existing ethanol subsidy by 5 years to 2015 and providing payments to lignocellulosic biomass suppliers for residues and energy crops. A payment of $20/ton of biomass is equivalent to paying producers a carbon credit of $40/ton of carbon dioxide recycled in the ethanol fuel life cycle.

Table 2-1. Achieving the 30x30 Goal

Factor	Description
World Oil	AEO 2006 high oil price case
Technology Progress	Accelerated targets under the 30x30 initiative
First-Generation Cellulose Technology	80% complete; $1.30/gallon nominal production price
Biomass Feedstock Subsidy	$20/dry ton payment through 2020
Ethanol Subsidy	$0.51/gallon subsidy extended through 2015

To understand how each of the factors in Table 2-1 affects market outcomes for ethanol, it is necessary to add the factors one at time. The results are summarized in Figure 2-4.

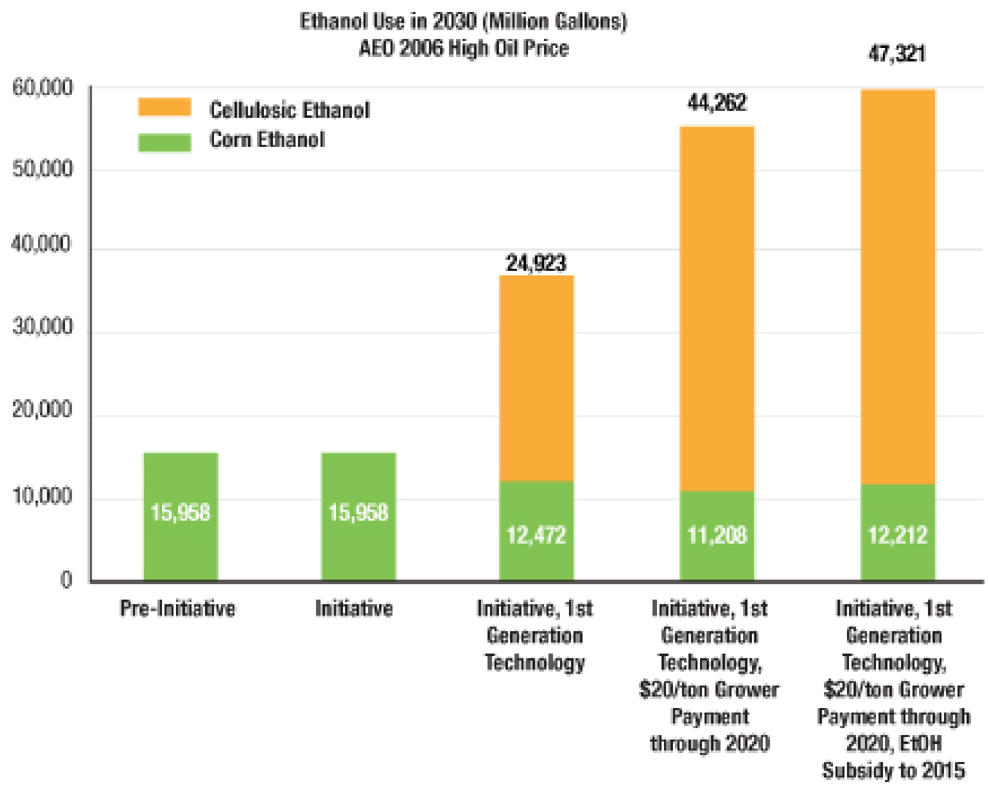


Figure 2-4. Applying Technology and Policy Levers to achieve 60 Billion Gallons/year of Ethanol from All Sources in 2030 in a High Oil Price Future

As shown in Figure 2-4 the scenario modeled in the BSM for achieving the 30x30 goal builds as follows:

<u>BSM Pre-Initiative Case:</u>
Prior to the President's Advanced Energy Initiative (Pre-Initiative) which had the $1.07/gallon cellulosic ethanol production target set for 2020, only corn ethanol is deployed to the maximum potential of ~ 16 billion gallons. Cellulosic ethanol does not achieve deployment under this scenario due to the fact that it never overcomes the risk hurdle for investors.

<u>BSM First Initiative Case:</u>
In the first initiative case, achieving the $1.07/gallon target is accelerated to 2012. As shown in Figure 2-4 this action has essentially no effect on ethanol deployment since cellulosic ethanol fails to clear the risk hurdle. Therefore under this scenario only starch-based ethanol is deployed up to the maximum potential of ~ 16 billion gallons.

<u>BSM Second Initiative Case:</u>
In the second initiative case, adding the 1st generation technology incentive provides for a government cost share of 50% for initial demonstration-scale facilities and 40% for initial full-scale facilities. In this case ~25 billion gallons of cellulosic ethanol capacity are deployed by 2030. Combined with a starch-based ethanol capacity of ~13 billion gallons, this equals a total ethanol deployment of ~ 38 billion gallons of ethanol by 2030. Although this amount is significant, it fails to achieve the 30x30 goal.

A particular point of interest is that under this scenario the BSM predicts a slightly lower volume of corn ethanol deployment by 2030 than in the earlier cases—12.5 billion gallons versus ~16 billion gallons in the earlier scenarios. This is due to the fact that under this scenario cellulosic ethanol becomes more attractive to investors than starch-based ethanol prior to starch-based ethanol achieving its maximum potential; hence investment capital is shifted to cellulosic ethanol. This is also true for the subsequent scenarios.

<u>BSM Third Initiative Case:</u>
In the third initiative case, adding a policy incentive of a payment for biomass to the grower of $20/dry ton through 2020 increases cellulosic ethanol deployed capacity to over 44 billion gallons by 2030, and when combined with the 2030 starch-based ethanol deployed capacity of 11.2 billion gallons, total ethanol capacity reaches ~55 billion gallons. Although this is close the 30x30 goal, the goal is still not achieved.

<u>BSM Fourth Initiative Case:</u>
Finally, in the fourth initiative case, by extending the current ethanol subsidy of a fixed $0.51/gallon of ethanol by 5 years (to 2015), ethanol production and use reaches just less than 60 billion gallons/year.

Figure 2-5 shows the ethanol deployment as a function of time for the four initiative scenarios. As shown in Figure 2-5, adding the additional policy incentives essentially accelerates cellulosic ethanol deployment in the marketplace by three to four years. This acceleration of cellulosic ethanol capacity has a significant impact in the total amount of deployed ethanol capacity by 2030. Although this data is not presented here, when the BSM was run out to 2050 all scenarios essentially predicted the same amount of deployed ethanol capacity, hence the BSM predicts the primary affects of the grower payment and ethanol subsidy policy incentives is to accelerate cellulosic ethanol capacity into the marketplace and will have minimal impact on total ethanol capacity in the long-term.

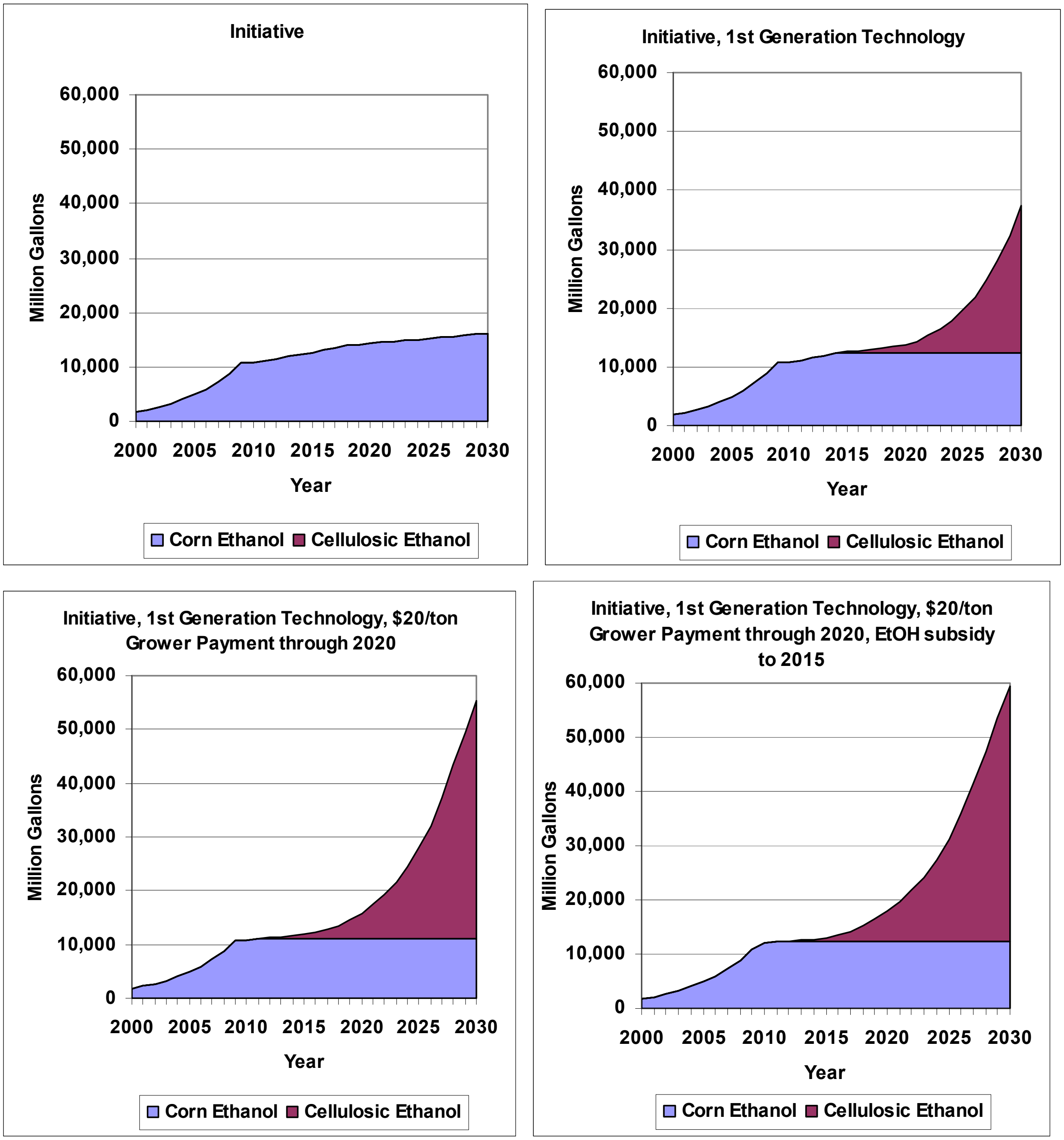


Figure 2-5: Ethanol Growth Rates under Different BSM Scenarios for AEO 2006 High Oil

2.2.1.2 Meeting the 30x30 Goal in a Reference Case Oil Price World

Although the AEO 2006 reference oil price case is a substantial departure from prior-year forecasts (reflecting a significant jump in oil price projections), it is based on the assumption that oil production can catch up with demand over the next 10 years to offset the oil price growth seen over the past few years. This increases the challenge for alternative fuels such as ethanol. When the same strategies as described in the previous section are applied under the AEO 2006 reference oil price case, 46 billion gallons/year of ethanol make it into the marketplace by 2030 (see Figure 2-6). Although the 30x30 goal is not achieved for AEO 2006 Reference Oil projections, we do achieve significant ethanol deployment at ~80% of what is achieved for AEO 2006 High Oil Price projections. Dynamic growth charts for ethanol production similar to the ones shown in Figure 2-6 are shown in Appendix B for the AEO 2006 Reference Oil case.

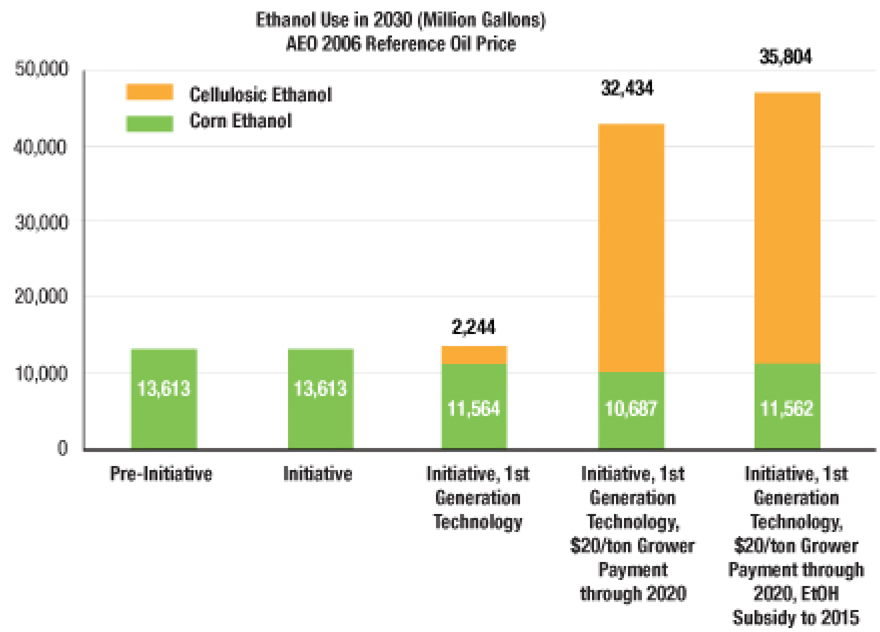


Figure 2-6. Applying Technology and Policy Levers to achieve 60 Billion Gallons/year in 2030 in a Reference Oil Price Future

2.2.2 The Role of Risk

One of the unique aspects of the BSM is that it quantitatively introduces investor attitudes toward risk. To understand how critical this risk translation is, consider what happens when the risk premium is removed (see Figure 2-7). Eliminating investor risk premiums dramatically increases ethanol deployment by 2030. In fact, the combination of the more aggressive President's Advanced Energy Initiative and an assumption of access to first-generation technology nearly meets the goal of 60 billion gallons in 2030, and adding the biomass payment easily exceeds 60 billion gallons —even under the reference case oil scenario.

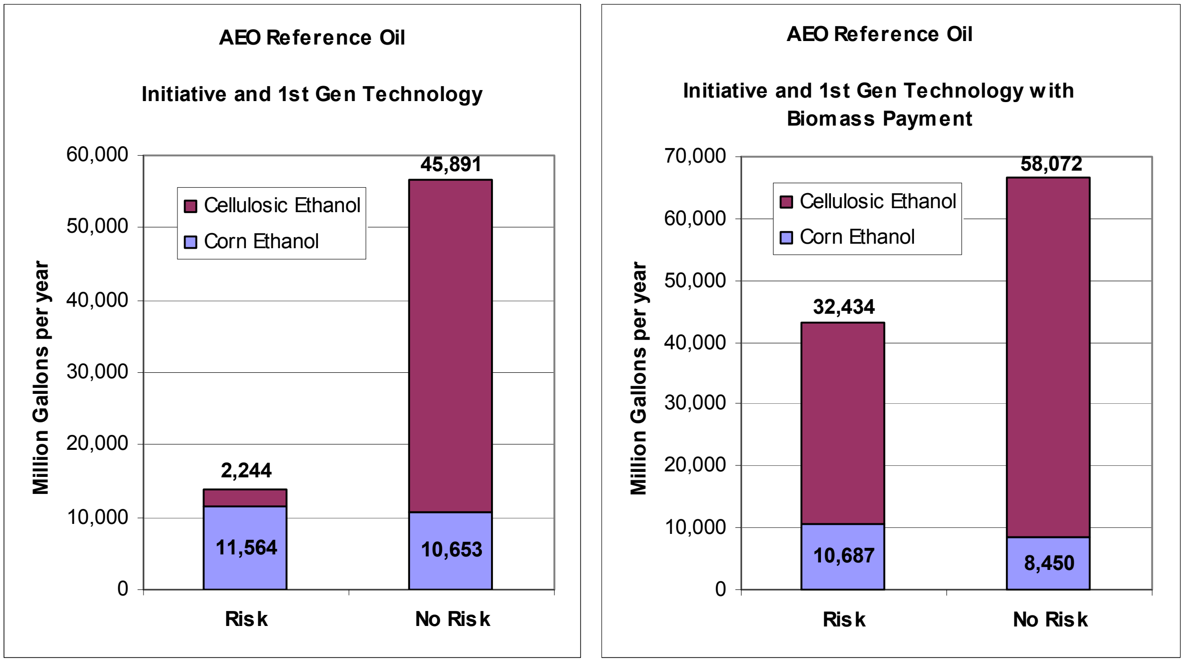


Figure 2-7. The Effect of Investor Risk Premiums

2.2.3 Ethanol in the Long Run

Meeting the 30x30 goal is not necessarily the ultimate outcome for ethanol. Once this aggressive goal has been met, ethanol production and use can continue to grow (see Figure 2-8). The BSM shows that, even when only half of the 2030 target is met, total ethanol production could reach 125 billion gallons/year by 2050, compared with 150 billion gallons/year for the same policy scenario under the high oil price.

2.2.4 U.S. Fleet Capacity for Ethanol

The BSM includes a vehicle fleet turnover module. In all of the analyses in this section, an aggressive scenario of FFV introduction is used, based on work done by the Union of Concerned Scientists for the Natural Resources Defense Council (Greene et al., 2005). Ethanol capacity in the U.S. fleet includes conventional vehicles able to legally operate on blends of up to 10% by volume ethanol in gasoline and FFVs that can operate on up to 85% ethanol. The aggressive scenario assumes a linear rise in the percentage of light-duty trucks and cars sold annually that are flex-fuel capable, from around 2.5% today to just more than 50% by 2015. Under these conditions, growth in fleet capacity for using ethanol, as shown in Figure 2-8, far outstrips the ability to deploy ethanol production facilities.

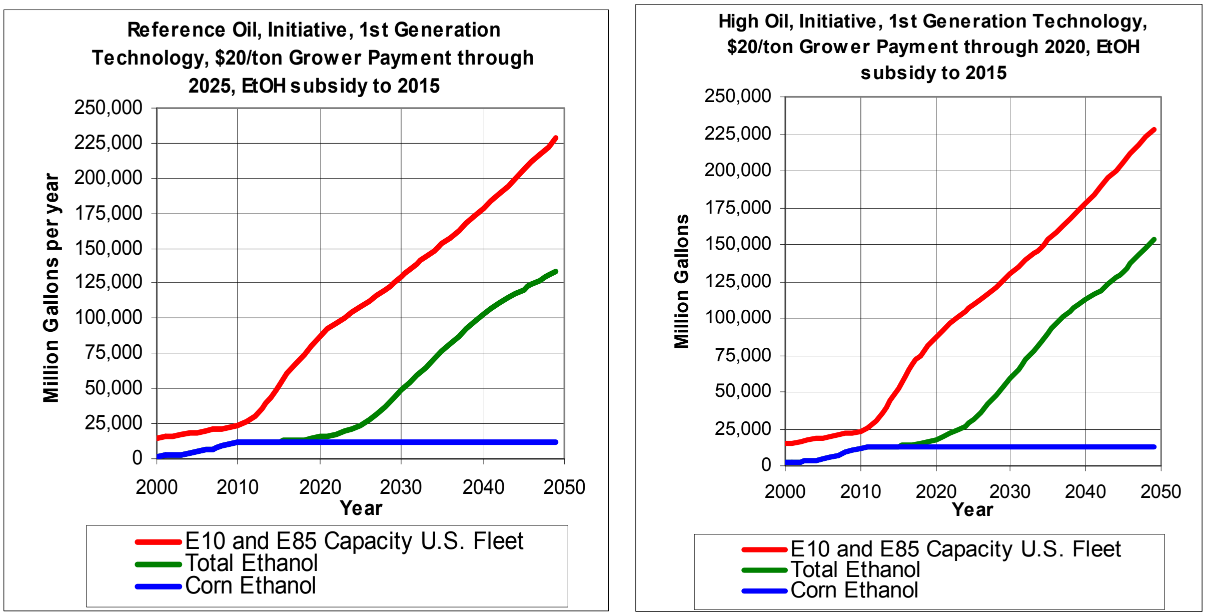


Figure 2-8. Long-term Effects of the 30x30 Initiative

2.2.5 Biomass Feedstock Production

Corn ethanol has an ultimate production potential of 9–17 billion gallons/year, depending on market and policy conditions (Appendix A). Beyond these levels, biomass for ethanol production becomes feasible. In the BSM model, feedstocks for cellulosic ethanol include agricultural residues, forest residues, and perennial energy crops (switchgrass or hybrid poplar). The BSM model assumes that production of cellulosic ethanol will begin by using agricultural and forest residues. Once consumption of residues reaches more than 100 million dry tons/year or approximately 10 billion gallons of cellulosic ethanol production, switchgrass production and use begins in the BSM. The predominant reason switchgrass/energy crop use lags agricultural residue use in the BSM is due to slower adoption rates of farmers, who must decide to dedicate land for 10–12 years to energy crop production (relative to the adoption rates of farmers who simply collect a portion of residues from corn and wheat already in the field).

2.2.6 Ethanol and Fuel Market Price Dynamics

The pricing of cellulosic ethanol is affected not only by total capital and operating costs but also by investors' required ROI, which in the BSM is a function of the relative risk of the technology compared with that of mature processes. Thus, in the early years, before R&D is complete, ethanol pricing is risk-inflated. Such prices are not realistic estimates of what investors think they will get; rather, they serve as a proxy for decision-making about the risk of the technology relative to the price that the market will bear. High ROIs and concomitant high price requirements simply translate into a "no go" decision on the part of the investor when the price is compared with prevailing value in the market. As pilot-plant work is completed and demonstration facilities come on line, the risk-adjusted price drops dramatically (see Figure 2-9).

In the BSM model, by 2012 risk-adjusted prices for cellulosic ethanol cross over market values, and investment in the first commercial-scale plants begins. Minimum selling price for cellulosic ethanol drops well below market value. This does not mean that ethanol prices will stay below fuel market value. The difference between market value and minimum price establishes the relative profitability of ethanol over gasoline. The higher these margins, the more rapidly investors build cellulosic ethanol facilities. Maintaining a reasonable margin is critical to rapid deployment of ethanol technology. This is why the target for ethanol pricing must be very aggressive, vis-a-vis gasoline. Furthermore, demand for feedstock eventually drives the minimum price for ethanol above market value, and industry growth slows (after 2046 in Figure 2-9). For this reason, ethanol conversion costs must be as low as possible to support increased feedstock prices as the industry grows.

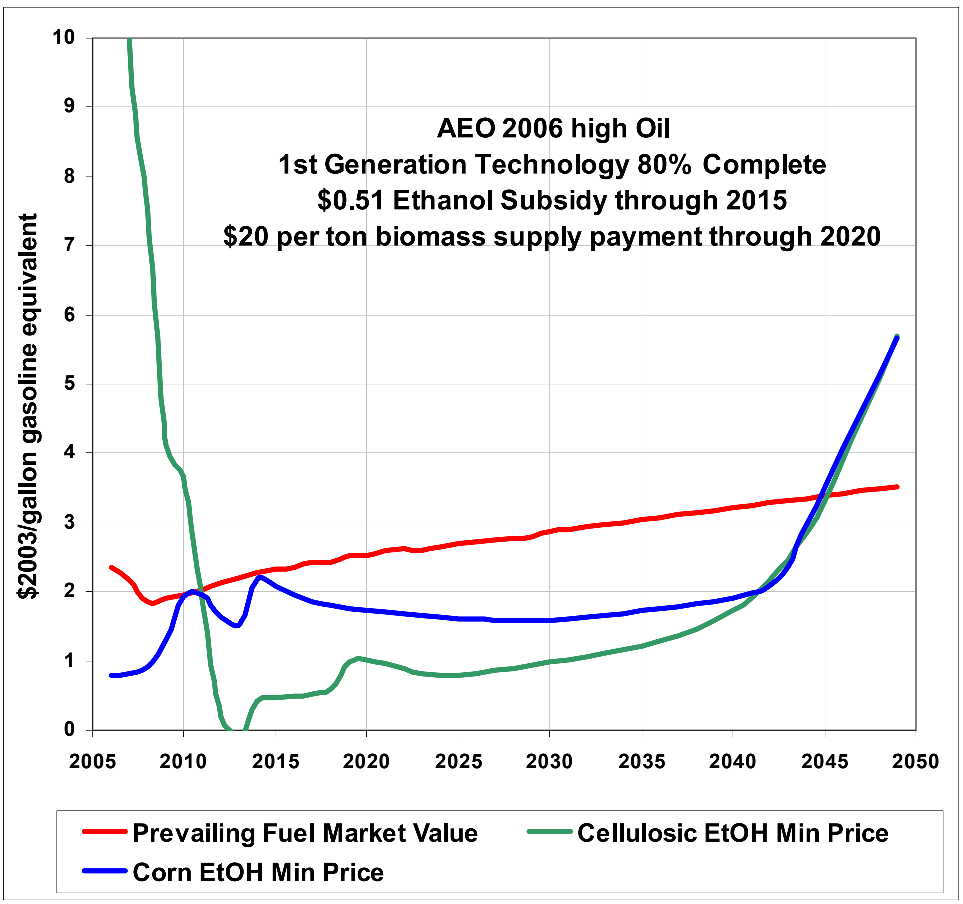


Figure 2-9. Price Dynamics for Ethanol and the Fuel Market

2.3 Summary

Ethanol can have major effects on the U.S. transportation fuel supply—especially by 2050. However, scenarios for meeting the 2030 goal associated with the 30x30 initiative call for aggressive government policy and the ability to build on decades of past research on cellulosic ethanol technology. The scenario that achieves the 30x30 scenario is one in which initial incentive payments of $20/dry ton are made to farmers, and a relatively brief extension of the federal incentive for ethanol is enacted. Although this is the only scenario in which the 30x30 goal is achieved, significant ethanol penetration at 80% of the 30x30 goal occurs for AEO 2006 reference oil price projections, which still makes significant strides towards energy security and decreased reliance on imported oil.

In the following sections of this scenario report the environmental and energy balance implications of this scenario will be analyzed, R&D pathways will be outlined for accomplishing the near-term $1.07 production target for competitive cellulosic ethanol by 2012 from both a biochemical and thermochemical route as well as long-term R&D targets for the advanced state of technology conversion cost targets necessary for utilizing the higher cost feedstocks to achieve the 30x30 goal. Finally the distribution and vehicle needs to achieve the 30x30 goal will be assessed.

3. Energy and Environmental Assessment

3.1 Wells-to-Wheels Analysis of Energy and Greenhouse Gas Emissions

To fully address the energy and environmental effects of the 30x30 scenario, we conducted life-cycle analysis for several ethanol production options. The analyses included all major activities associated with producing and distributing biomass feedstocks and ethanol and the use of ethanol in motor vehicles. Life-cycle analysis of vehicle/fuel systems is often called "wells to wheels" (WTW) analysis (or, more precisely, "farms to wheels" analysis for biofuels).

The primary tool used in the ethanol life-cycle analysis is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by Argonne National Laboratory (ANL). Researchers at ANL began developing the GREET model in 1995, with support primarily from DOE's Office of Energy Efficiency and Renewable Energy (EERE). Argonne released the first version of the GREET model 1.0, in June 1996. The Microsoft Excel-based, multidimensional spreadsheet model addresses the life cycle analytical challenges associated with alternative fuels (including ethanol) and vehicle technologies.

For a given vehicle and fuel system, GREET calculates:

- Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (i.e., petroleum, natural gas, and coal), and petroleum
- Emissions of carbon dioxide-equivalent greenhouse gases, or GHGs (primarily carbon dioxide, methane, and nitrous oxide)
- Emissions of five criteria pollutants: volatile organic compounds (VOCs), carbon monoxide, nitrogen oxide, particulate matter smaller than 10 microns, and sulfur oxides. These emissions are further separated into total and urban emissions.

For the 30x30 analysis we used the latest version of the GREET model, GREET 1.7 to generate results for all the items listed above. This model is capable of analyzing more than 90 transportation fuel pathways and 75 vehicle/fuel systems (Wang et al., 2005). However, only fossil energy consumption, petroleum consumption, and GHG emissions are presented in this section. Complete results are presented in Appendix H.

Although the 30x30 effort addresses many ethanol production technologies, because of data and resource limitations, life-cycle simulations were conducted only for selected ethanol production options. In particular, we examined four feedstocks: corn, agricultural residues, switchgrass, and forest residues.

Corn-based ethanol currently accounts for essentially all of U.S. ethanol, and it will continue to play a major role in the U.S. fuel ethanol market both in the near- and long-term hence corn was included as one of the life-cycle simulations. The cellulosic feedstocks for the life-cycle simulations were chosen according to the DOE-USDA Billion Ton study (Perlack et al. 2005). We used the following assumptions from the Billion Ton study:

- Approximately 550 million tons of crop residues could be available each year (about half of which is corn stover)
- Nearly 400 million tons of perennial crops such as switchgrass could be available in the future
- About 370 million tons of forest residues could be available.

These cellulosic biomass feedstocks, in addition to corn grains, could support large-scale ethanol production. To compare ethanol's relative energy and emission merits, life-cycle analysis of petroleum gasoline was also included. Thus, we analyzed five life-cycle cases:

1. Petroleum gasoline (the baseline fuel)
2. Corn to ethanol
3. Corn stover (representative of agricultural residues) to ethanol through the biochemical conversion process
4. Switchgrass to ethanol through the biochemical conversion process
5. Forest residues to ethanol through the thermochemical conversion process.

Ethanol production technology will advance over time. This is especially true for the three cellulosic ethanol production options above. To address technology advancement, life-cycle analysis was conducted for each of the cases in 2012 and 2030 separately.

The life-cycle input parameters were collected from several sources:

- The petroleum gasoline and corn ethanol cases for 2012 and 2030 used data accumulated from previous analyses.
- The three cellulosic ethanol cases in 2012 used ethanol production process data for the 2012 design case for both the biochemical and thermochemical case (Aden et al., 2002) (Spath and Dayton, 2003).
- The two biochemical conversion cellulosic ethanol cases (corn stover and switchgrass to ethanol) in 2030 simulated the case of ethanol production with lignin used in a combined-cycle gas turbine for electricity co-generation. (Although technologies such as steam boilers can be used for electricity co-generation, combined-cycle gas turbines with gasification of biomass residues represent advanced combustion technology. In fact, this technology is now being installed in corn-based ethanol plants to generate steam and electricity from gasified biomass and distillers dry grains.)
- The two cellulosic ethanol cases adopted process data generated from the Role of Biomass in America's Energy Future (RBAEF) project for a similar cellulosic ethanol case (Wu, Wu, and Wang 2006).
- The thermochemical cellulosic ethanol case (forest residues to ethanol) in 2030 relied on preliminary process data consistent with the thermochemical advanced state of technology (Section 4.2.2).

GREET life-cycle simulations produced energy and emissions results for each million British thermal units (mmBtu) of fuel produced and used. Figure 3-1 shows life-cycle fossil energy use for the four ethanol options and gasoline. Fossil energy includes petroleum, coal, and natural gas. Relative to gasoline, corn-based ethanol achieves moderate reductions in fossil energy use, but the three cellulosic ethanol options achieve significant reductions. Figure 3-2 shows life-cycle petroleum use results, which are a subset of the fossil energy use results. As the figure shows, all four ethanol options result in huge reductions in petroleum use relative to the petroleum gasoline case. Figure 3-3 compares life-cycle GHG emissions of ethanol and gasoline. GHG emissions are in grams of carbon dioxide-equivalent emissions of carbon dioxide, methane, and nitrous oxide weighted with their global warming-potential factors. As the figure shows, although corn-based ethanol achieves moderate reductions in GHG emissions, cellulosic ethanol achieves very large ones.

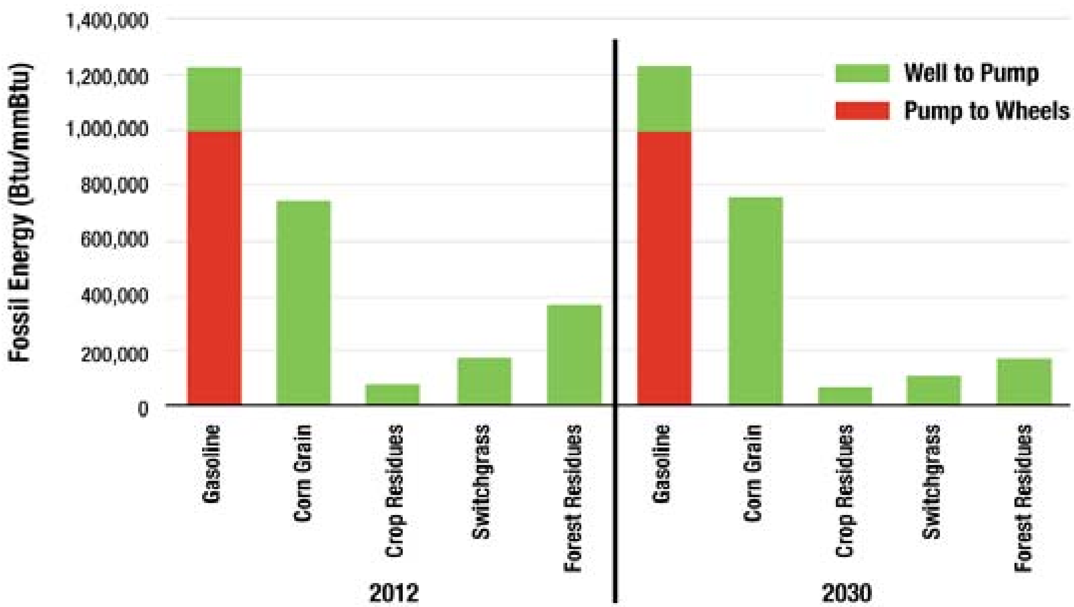


Figure 3-1. Life-cycle Fossil Energy Use of Ethanol versus Gasoline

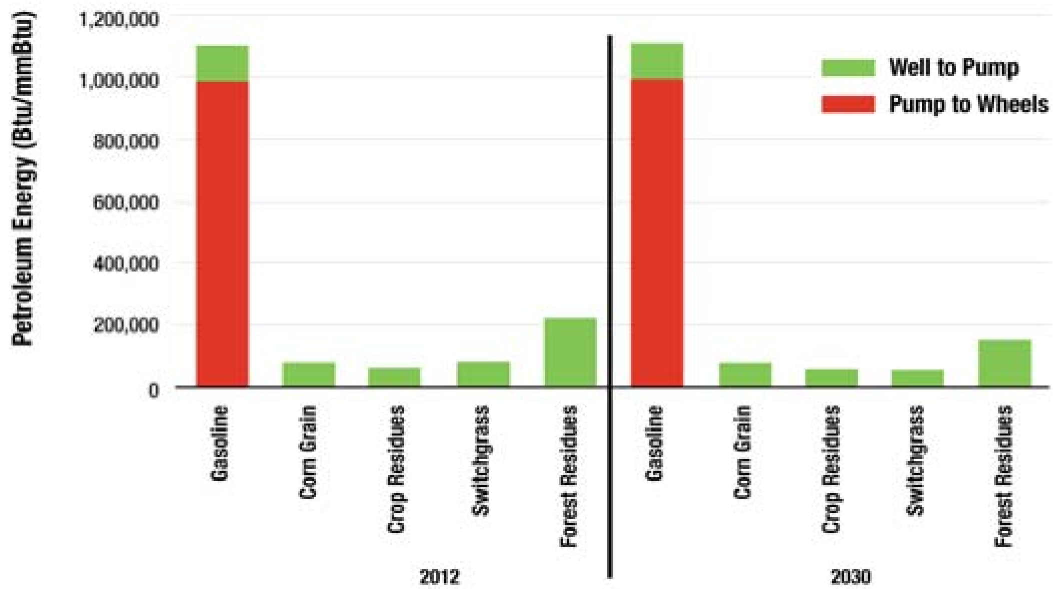


Figure 3-2. Life-cycle Petroleum Use of Ethanol versus Gasoline

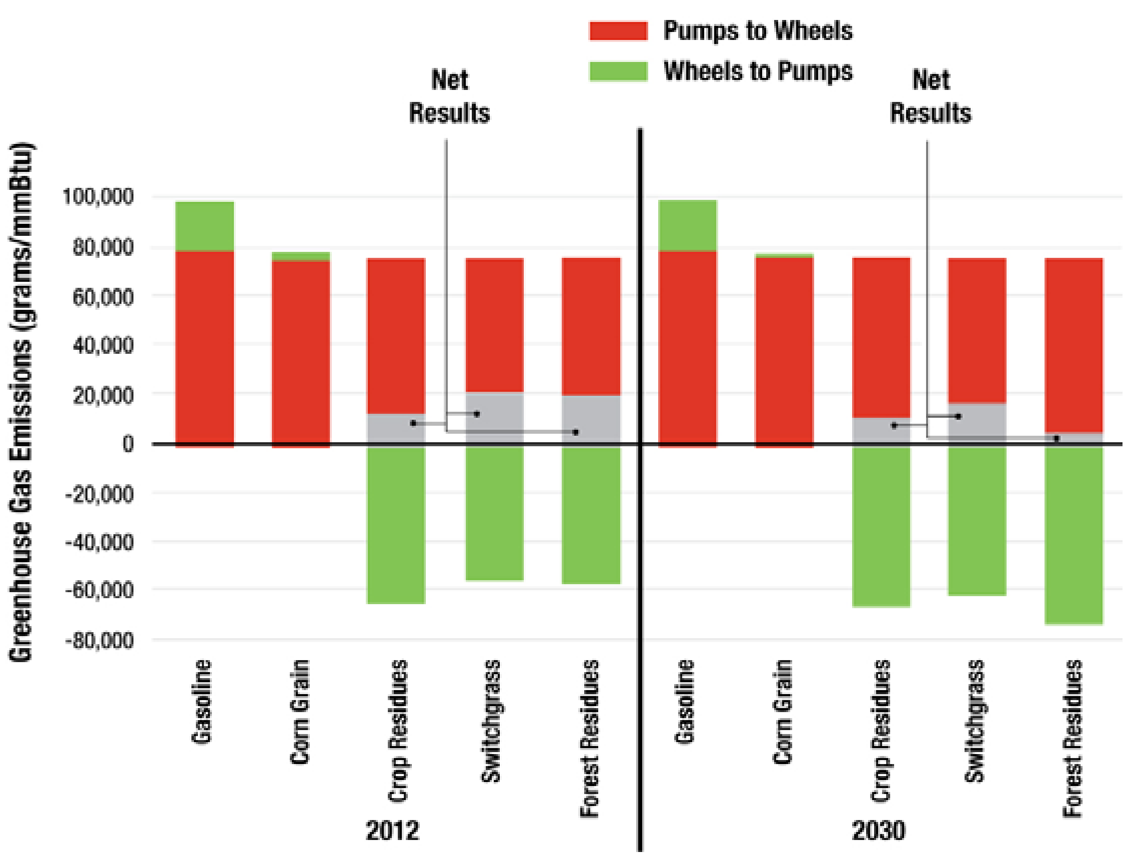


Figure 3-3. Life-cycle Greenhouse Gas Emissions of Ethanol versus Gasoline (carbon dioxide-equivalent emissions of carbon dioxide, methane, and nitrous oxide)

Differences in energy use and GHG emissions exist among the three cellulosic ethanol options. For example, there is high fossil energy and petroleum use in forest residue-based ethanol. This is because of the use of natural gas and electricity in forest residue ethanol plants (especially in 2012) and significant diesel fuel use for stumpage, collection, and transportation of forest residues. Further, forest residue-based ethanol has similar or reduced GHG emissions relative to other cellulosic ethanol options. This is because forest residue-based ethanol is not associated with soil nitrous oxide emissions whereas the other two options are.

3.2 Annual Reductions in Oil Consumption and Greenhouse Gas Emissions Caused by Ethanol Use

In this section, the estimated annual ethanol supplies under the EIA reference case (the low ethanol supply case) and the EIA high oil price case (the high ethanol supply case) are used to estimate annual reductions in oil use and GHG emissions caused by ethanol use.

The VISION model, developed at ANL, was used to match ethanol demand by motor vehicles with ethanol supply under each case. The VISION model uses vehicle survival and age-dependent usage procedures to track vintage-specific vehicle stock and usage. The model develops estimates of light- and heavy-duty vehicle stock composition, vehicle miles traveled, and energy use. The current version can simulate conventional vehicles and six advanced-technology vehicles in car and light truck categories (Singh, Vyas, and Steiner 2004). The model was calibrated to match EIA's 2006 *Annual Energy Outlook* projections, which are provided only to 2030. The projections were therefore extended to 2050 through a collaborative effort with DOE EERE Office of Planning and Budget Analysis. The VISION model has been used extensively by EERE to evaluate the effects of new technology.

In VISION simulations, we assumed that ethanol will penetrate the gasoline market for the light-duty vehicle fleet, including passenger cars, sport utility vehicles, and light-duty trucks. The VISION simulations assume that ethanol will gradually penetrate the gasoline market, with low-level ethanol blends up to E10 reaching 100% of the gasoline market by 2020. We then assumed that the remaining ethanol supply (i.e., the amount that exceeds E10 demand) will be used in FFVs in ethanol blends up to E85. Light-duty vehicles have high survival probability through their first 10 years. Consequently, FFVs sold in earlier years may not have enough fuel ethanol available to operate at 85% volume. In this situation, we assumed FFVs would use ethanol blends of less than 85% ethanol or that some FFVs will operate on gasoline only, as most FFVs do now. The resulting ethanol consumption will match production estimates, but the average ethanol content of FFV fuel may be less than 85%. Furthermore, the same gasoline-equivalent fuel economy was assumed for E85 FFVs and gasoline vehicles accounting for the lower Btu content of E85.

With these assumptions, the VISION model estimated that the number of FFVs on the road in 2050 will reach 207 million under the low ethanol supply case and 244 million under the high ethanol supply case, respectively accounting for 52.6% and 62.1% of the total light-duty fleet of that year. Annual new FFV sales reach a 50% share of the new light-duty vehicles market in 2038 under the low ethanol supply case and in 2032 under the high ethanol supply case. Historical data of new vehicle technology penetration show these penetration schemes can be achieved without much difficulty. This implies that ethanol supply, not ethanol demand by the FFV market, will be the main determinant of ethanol's share in the transportation fuel market.

The simulated annual consumption estimates for gasoline and ethanol were used to compute oil demand and life-cycle GHG emissions. To accomplish this, we used the life-cycle output of petroleum use and GHG emissions from GREET (as presented in Section 3.1). For VISION simulations, the split between corn ethanol and cellulosic ethanol was based on supply estimates given in Section 2 for both reference oil and high oil (Figures 2-4 and 2-6). For the three types of cellulosic ethanol, we assumed that 30% is produced from forest residues, 35% from agricultural residues, and the remaining 35% from switchgrass.

Figure 3-4 shows life-cycle oil use under three scenarios: (1) the base case, (2) the low ethanol supply case, and (3) the high ethanol supply case. As shown in the figure, by 2030, the low ethanol supply case helps reduce oil use by about 2 million barrels/day, and the high ethanol supply case achieves an additional reduction of 0.8 million barrels/day. By 2050, ethanol can help reduce oil use by 6.5 to 7.5 million barrels/day.

The resultant GHG emissions, in million metric tons (MT) carbon dioxide-equivalent per year, are shown in Figure 3-5. By 2030, the use of ethanol could reduce GHG emissions by 220–340 million MT/year. By 2050, the reduction is 960–1,110 million MT/year. For comparison, VISION estimated that total life-cycle GHG emissions of the U.S. light-duty vehicle fleet were 1,530 million MT in 2005.

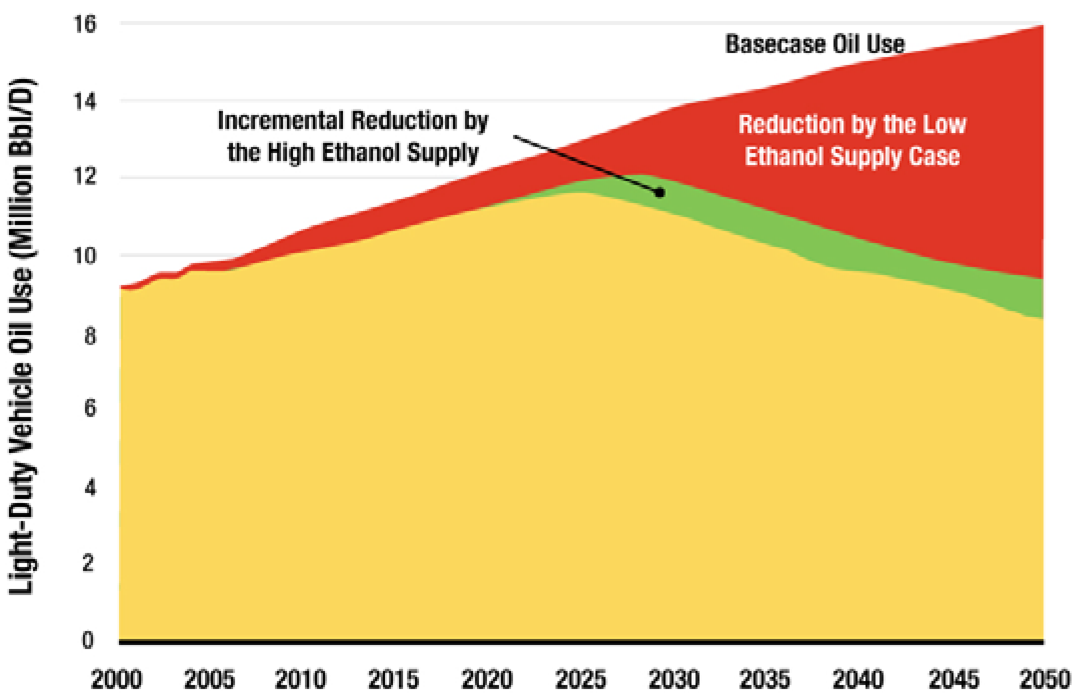


Figure 3-4. Life-cycle Oil Use under the Three Cases

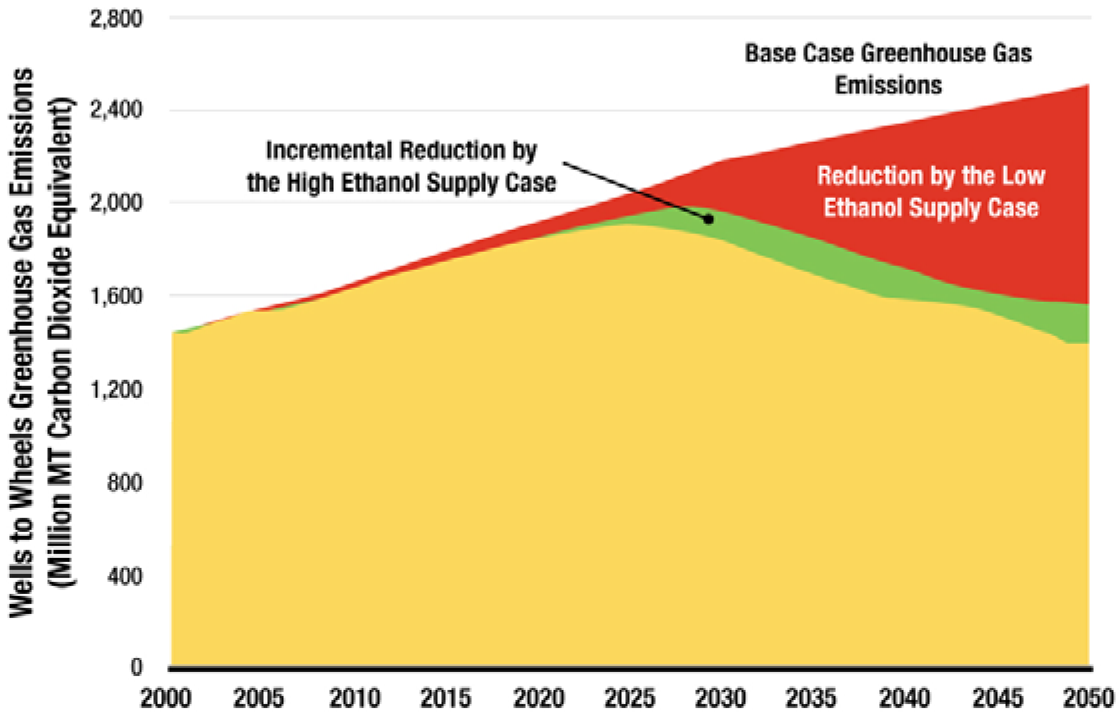


Figure 3-5. Life-cycle Greenhouse Gas Emissions under the Three Cases

3.3 Other Potential Environmental Issues

The successful implementation of this scenario will require sustainable processes that minimize impacts on the environment and avoid depleting resources needed in other sectors of society. Land use and availability, biodiversity, water resource management, and solid, liquid, and air emissions must be considered. In addition, environmental impact analyses must consider feedstock production, feedstock collection and storage, biofuels production, and product storage and distribution.

3.3.1 Land

The biggest land issues are associated with feedstock production. Using long-term, conservative production targets of 10 dry tons of biomass/acre with ethanol yields of 100 gallons of ethanol/dry ton, approximately 20 million acres of land will be needed to produce the 20 billion gallons of cellulosic ethanol from switchgrass using the feedstock allocations assumptions stated in Section 3.2. Although this amount of land is only slightly more than 5% of current cropland (excluding cropland that is inactive or idle and pasture) of about 340 million acres it is still a significant amount of land. If we assume that prime arable land will remain dedicated to food and feed, then biomass production will increasingly require sub-prime and marginal land of poorer soil quality and insufficient water resources. Lower-quality land will reduce biomass crop density and, therefore, increase the infrastructure and costs associated with collection (Tuskan et al. 2004).

Further, there are potential issues associated with each feedstock type. For example, if inactive land enrolled in the Conservation Reserve Program land and undisturbed forests are used for energy crops, feedstock production could affect native biodiversity. If agricultural and forest residues are primary feedstocks, then large increases in land use could be avoided, but the collection of corn stover could negatively affect soil quality. The amount of stover collected must be limited to avoid soil depletion and was taken into account in the life-cycle analysis presented earlier. On the other hand, perennial crops such as switchgrass reduce fertilizer inputs and reduce land and water impacts.

Another land issue concerns storage and production facilities. Depending on the success of densification efforts, the land requirements for crop residue or switchgrass could be substantial. (Wood and grain are significantly more dense and therefore do not pose a storage problem. Moreover, woody resources can be stored "on the stump.") Because feedstock collection will be conducted in a harvest window but ethanol production will be conducted most of the year, a distributed storage system of lower-density biomass will require regular shipments from a storage grid (Schlicher 2006). This will increase truck traffic in rural areas. Production facilities, in contrast, do not have large footprints. They should have land impact issues only in specific cases. Finally, depending on chemical requirements, biomass conversion facilities may generate wastes such as gypsum that have little market value and may require land filling.

3.3.2 Water

Water management includes the volume and quality of water required for, and released by, ethanol production activities. As with land, the biggest water management issues are associated with feedstock production.

The most productive portion of the Corn Belt does not require irrigation. However, extending biomass production to marginal lands may require irrigation. For energy crops that cannot be diverted to the food and feed sectors, opportunities to use "impaired waters," such as waters produced from electric power plants, could be a net benefit of biomass production. In addition, the use of perennial crops that retain their nutrients can reduce releases to water systems. In the future, energy crops with the capability to deep root and draw from underground aquifers could increase biomass production without requiring additional water resources.

A related issue is the effect of agricultural fertilizer runoff on local and regional water systems. These effects have been well documented, but shifting to hybrid seeds that require reduced nitrogen will reduce impact on water quality (Illinois Corn Growers Association 2005).

In production facilities, biochemical conversion uses significant water. Current grain-to-ethanol processes require about three gallons of water for every gallon of ethanol produced (Swain 2006). But with treatment and recycle, water inputs can be minimized. However, these processes will still require some water release and "blowdown" to avoid a buildup of impurities.

Thermochemical processes do not have significant water requirements and could be net producers of water during feedstock drying. In future integrated biorefineries, synergies between biochemical and thermochemical processes could greatly reduce water input requirements. For example, thermochemical drying could supply most of the makeup water for plants.

3.3.3 Emissions

In the emissions arena, biofuel production facilities could have a larger impact than feedstock production activities. As ethanol plant size increases, some plants may fall under the category of "major pollutant emitter," which requires increased permitting, monitoring, and other oversight. Potential emissions that should be considered include ash and inorganics from thermochemical processes, nitrogen oxides, sulfur oxides, and VOCs, and particulate air emissions, as presented in Appendix H.

Emissions and their impact will be strongly dependent on the feedstock, conversion process, and facility location. For example, black liquor residues in pulp and paper mills have sulfur contents, which could potentially result in significant sulfur oxide emissions.

3.4 Benefits of the Integrated Biorefinery

Integrated biorefineries offer opportunities to reduce the environmental impact of biofuel production (Energy-Water Nexus 2006). Process integration and intensification will reduce energy and water inputs as well as net solid, liquid, and air emissions. In addition, improvements in process efficiency will reduce the land required to produce the required amounts of feedstock.

In a sustainable process, biomass will be collected without degrading land, soil, water, or biodiversity. In the future, integrated biorefineries will produce ethanol and other products with potentially zero liquid discharge, limited air emissions, and the efficient use, recycle, or disposal of solids.

4. Cellulosic Ethanol Production

Central to the success of the 30x30 goal is the availability of biomass resources and the efficiency with which these resources can be converted into transportation fuels. Aligning these components to replace 30% of 2004 motor gasoline demand by 2030 will require, above all else, process and technology flexibility.

The feedstock resource assessment in the "Billion Ton" study (Perlack et al. 2005) validates the feasibility of achieving the 30x30 goal, provided R&D efforts overcome technical barriers to the development of economically viable biomass conversion technologies. The feedstock resource base, however, includes a variety of regionally specific biomass materials with a range of chemical and physical properties. Figure 4-1 shows the distribution of feedstock resources described in the "Billion Ton" study.

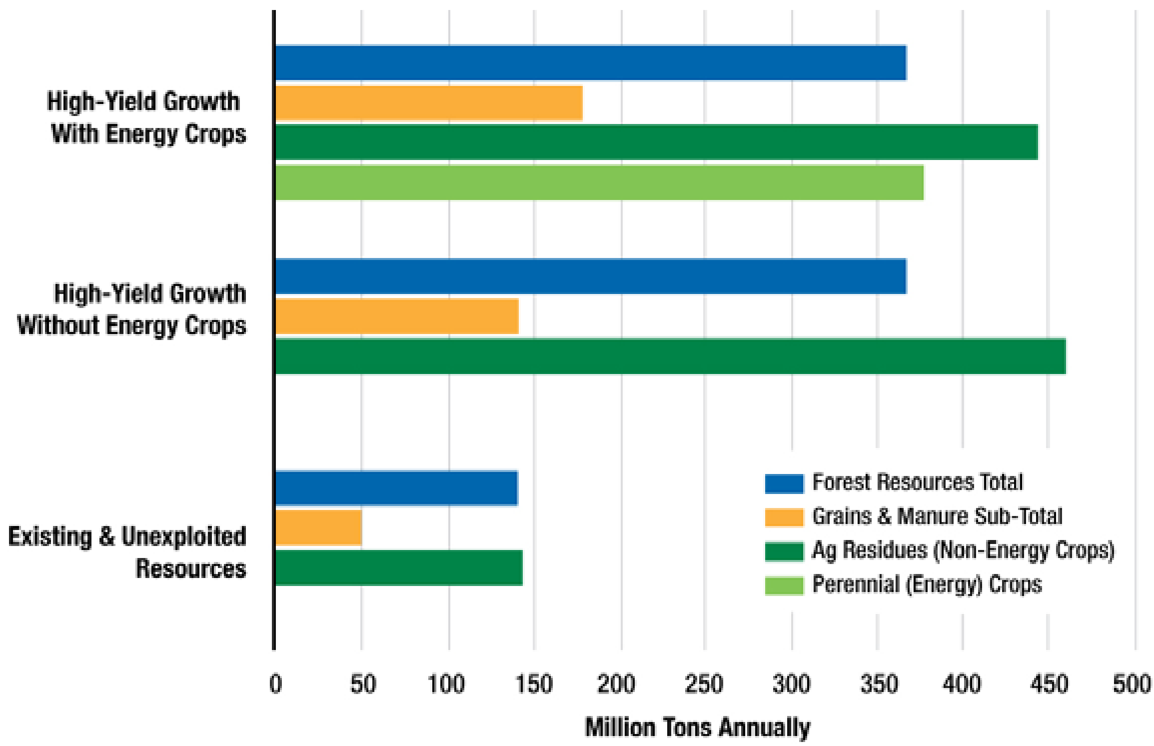


Figure 4-1. Distribution of Feedstock Resources

This implies that the conversion technologies of future integrated biorefineries will be a function of the available feedstock resources. For this reason, cellulosic ethanol production technology must be sufficiently diverse to optimize the conversion of multiple biomass resources to fuel.

In this section, two conversion technologies that can potentially process the projected feedstock resources are considered (see Figure 4-2). Both of these routes have several variations, but the main difference is in the primary catalysis system.

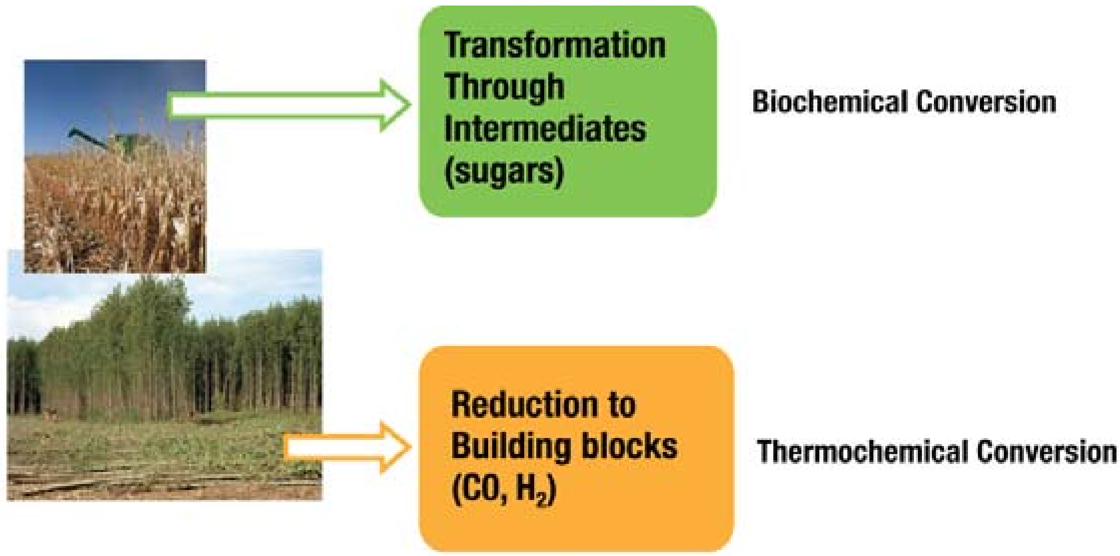


Figure 4-2. Primary Conversion Routes for Cellulosic Biomass

Biochemical conversion uses biocatalysts (such as enzymes and microbial cells), heat, and chemicals to convert biomass first to an intermediate sugar stream and then to ethanol and co-products such as heat, power, and chemicals. Thermochemical conversion reduces biomass to a fundamental chemical building block, syngas (carbon monoxide and hydrogen), that can be converted into ethanol and other products through fuel synthesis processes.

For this discussion, forest residues—from small-wood forest thinnings or residues such as "hog fuel" from the forest products industry—are considered primarily for thermochemical conversion because of their anticipated higher lignin content. Agricultural residues, in contrast, are considered primarily for biochemical conversion technologies. These resources are expected to have a more uniform chemical composition because they are derived from cultivated crops that can be genetically engineered or selected for properties more amenable to biochemical conversion technologies (such as low recalcitrance or high cellulose or xylan content). This also holds for energy crops. Biomass grown specifically for transportation fuel production can be engineered or selected to have the most desirable chemical and physical properties for a conversion technology. In addition, increasing the biomass resource base that can be biochemically converted to fuels provides an additional resource: lignin-rich fermentation residues that can be used for combined heat and power production or converted to biofuel in advanced, integrated biochemical-thermochemical biorefineries.

The 30x30 goal of developing 60 billion gallons of ethanol capacity by 2030 highlights the need for optimization of all aspects of biofuels production, including:

- Conversion technology-specific feedstock resources
- Feedstock production, storage, and distribution
- Biochemical conversion technologies
- Thermochemical conversion technologies.

As technology develops, existing conversion routes will mature and others will be developed, including some with the ability to reduce the energy expenditure of the overall biomass-to-ethanol process. Although specific scenarios are considered in this section, it is the responsibility of the developing bioenergy industry to use opportunistic resources with specific conversion technologies to produce products (such as fuels, chemicals, materials, and power) that meet strategic business goals.

4.1 Feedstocks

The emerging biorefining industry is dependent on a large and sustainable supply of biomass resources provided at an effective cost and quality. The Billion Ton study found that the biomass feedstock resource potential in the United States is more than sufficient to meet the 30x30 goal. About 368 million dry tons of sustainably removable biomass could be produced on forest lands, and about 998 million dry tons (including agriculture residues and new perennial crops) could come from agricultural lands (see Figure 4-3). This resource potential could be available roughly around the mid-21st century.

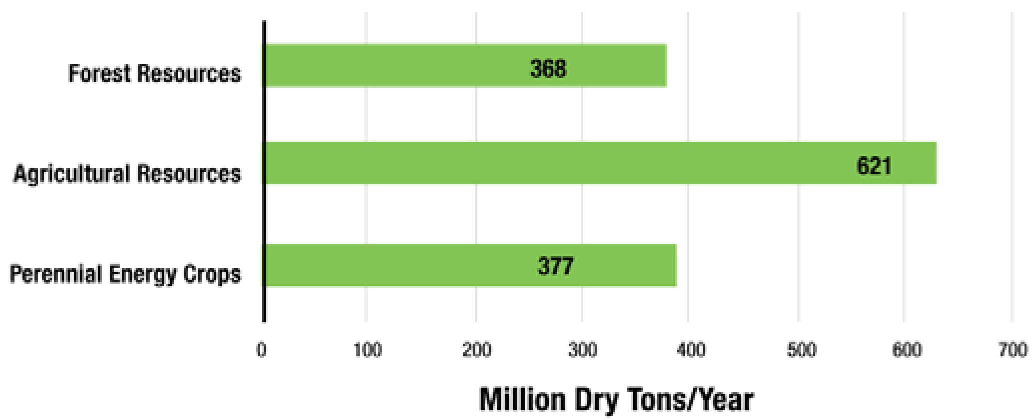


Figure 4-3. Agricultural and Forest Lands Resource Potential

4.1.1 Feedstock Accessibility

The ethanol price target of $1.07/gallon by 2012 is based on a total delivered biomass feedstock cost of $35/dry ton. This 2012 feedstock cost target can be subdivided into a $10/dry ton grower payment (or "stumpage fee" for forest resources) to cover the biomass value and a $25/dry ton payment for feedstock supply system costs, which include harvest and collection, storage, pre-processing, and transportation and handling. The $10/dry ton grower payment is much too low to cover production costs for perennial energy crops. It is estimated that, from the 1.3-billion-ton potential, as much as 130 million tons could be accessed for a grower payment of or less than or equal to $10/dry ton. Therefore, technology advancements that reduce feedstock supply system costs to $25/dry ton for each of the major agricultural and forestry feedstock resource types will result in a 2012 biomass resource sufficiently large to establish both biochemical and thermochemical biorefining capacity in every region of the United States (see Figure 4-4).

Figure 4-4. Accessible Agricultural and Forest Resources with Biorefinery Capacity Potential in 2012

As the industry expands from grain ethanol to cellulosic ethanol, it is expected that agricultural crop residues and forest logging residues will be the first resources developed for biorefining. Energy crops will become integrated into the agricultural cropping system as the biorefining industry matures and creates demand for them. The increase in energy crop production will likely occur as land managers (e.g., farmers and plantation foresters) use the additional crop options provided by the biomass energy market to maximize the productive capacity and economic returns of the land they manage. Collaborations with USDA and regional partners will become critical in the development of sustainable biomass production and crop rotation strategies for existing and new biomass resources.

The expanding use of lignocellulosic biomass resources will create a demand for them, which will result in biorefineries paying more to access larger tonnages of more expensive feedstocks (i.e., resources that require more than a $10/dry ton grower payment). However, feedstock demand will always be limited by the price the biorefining industry can pay while remaining competitive in the ethanol fuel market. Initially, government policies and programs may be the means to access higher-value feedstocks. Up to and beyond the 2030 time frame, technology advancements will reduce biomass processing costs, which will then provide increased purchasing power for biorefineries to access higher-value biomass feedstocks. This strategy of improving supply and conversion technologies to purchase higher-value feedstocks is well-established in other processing and refining industries (Stoppert 2005). This combination of policy and technology advancement will develop a U.S. biomass resource large enough to support the 30x30 goal (see Figure 4-5).

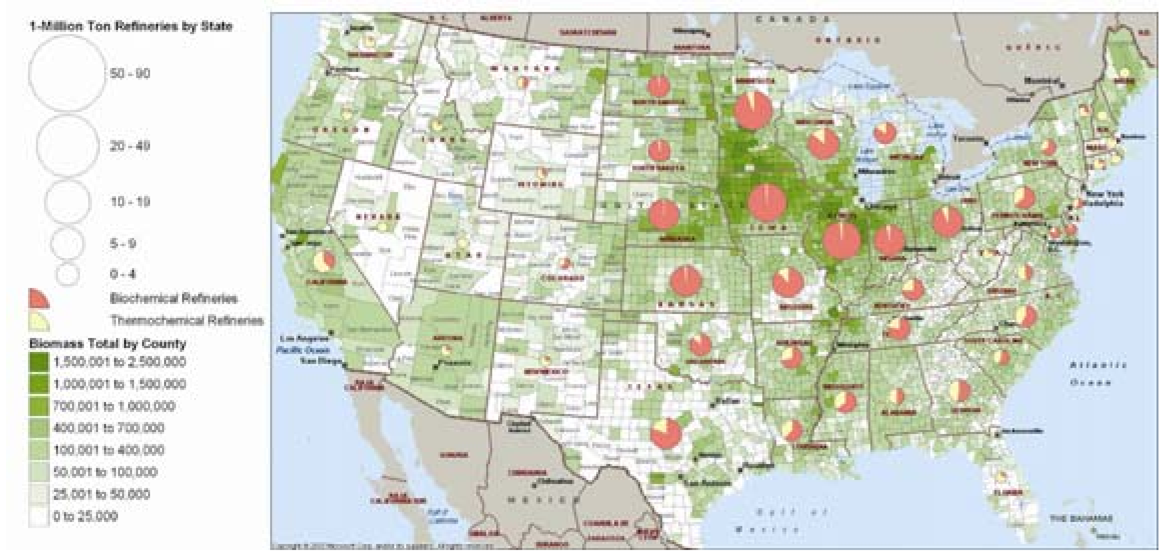


Figure 4-5. Accessible Agricultural and Forest Resources with Biorefinery Capacity Potential to Produce 60 Billion Gallons of Ethanol in 2030

4.1.2 Feedstock R&D Pathway

Feedstock R&D encompasses all the unit operations necessary to move biomass feedstocks from the land to the conversion process of the biorefinery (Cushman et al. 2003) (see Figure 4-6). General descriptions of the feedstock R&D pathway, the state of technology, and R&D and technology needed to achieve and validate the $35/ dry ton cost target are presented in this section.

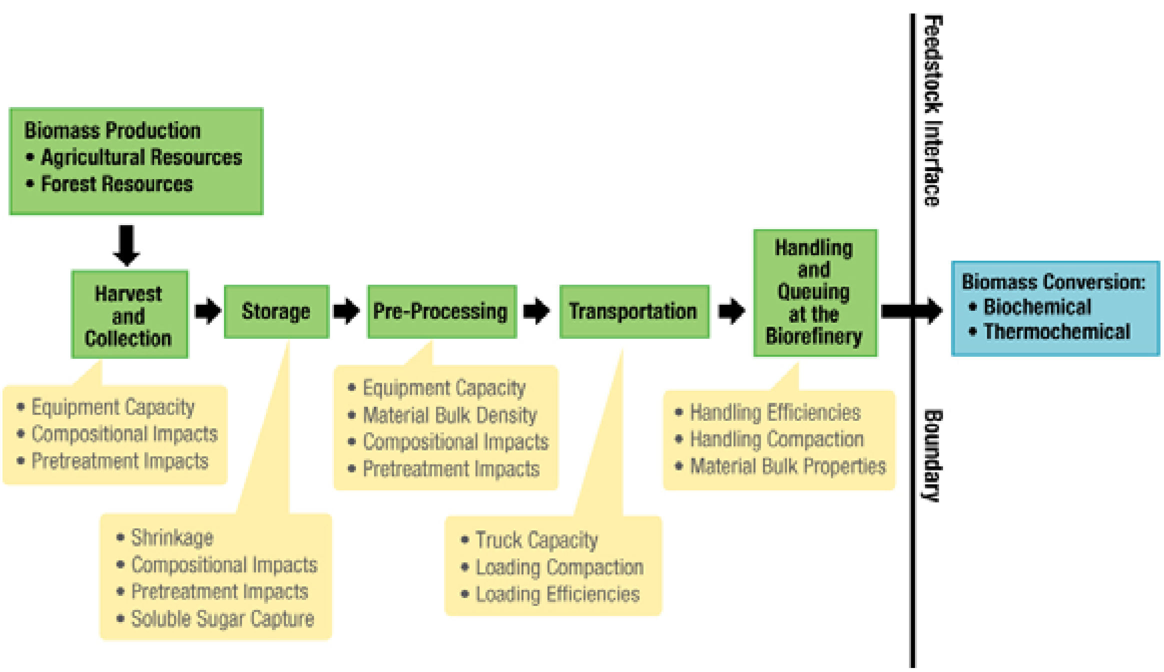


Figure 4-6. Supply Schematic for $35/Dry Ton Feedstock

Biomass production is the beginning of the feedstock supply chain. It involves producing biomass feedstocks to the point of harvest. Production addresses important factors such as selection of feedstock type, land use issues, policy issues, and agronomic practices that drive biomass yield rates and directly affect harvest and collection operations.

Harvest and collection encompasses all operations associated with getting the biomass from its source to the storage or queuing location. In addition to obvious operations such as cutting (or combining, swathing, or logging) and hauling, this often includes some form of densification such as baling, bundling, or chipping to facilitate handling and storage.

Storage and queuing are essential operations in the feedstock supply system. They are used to deal with seasonal harvest times, variable yields, and delivery schedules. The objective of a storage system is to provide the lowest-cost method (including cost incurred from losses) of holding the biomass material in a stable, unaltered form (i.e., neither quality improvements nor reductions) until it is called for by the biorefinery.

Prior to conversion, the feedstock must be pre-processed to physically transform it into the format required by the biorefinery. Pre-processing can be as simple as grinding and formatting the biomass for increased bulk density or improved conversion efficiency, or it can be as complex as improving feedstock quality through fractionation, tissue separation, and blending.

Transportation generally consists of moving the biomass from the storage location to the biorefinery via truck, rail, barge, or pipeline. The system used will directly affect how the feedstock is handled and fed into the conversion process. Transporting and handling methods are highly dependent on the format and bulk density of the material; this makes them tightly coupled to each other and all other operations in the feedstock supply chain.

Significant advances have been made to transform the feedstock supply process from traditional technologies used in smaller distributed livestock, forage, and wood products industries to an assembly system specifically designed for the biorefinery industry. However, much work remains.

Feedstock infrastructure development is difficult because equipment, methods, and logistics vary not only among resources (e.g., agricultural residues versus forest residues) but also among geographic regions (e.g., dry agricultural residues in the West versus wet agricultural residues in the Midwest and Northeast). Consequently, the feedstock supply infrastructure must be developed for each class of biomass resource.

These classes, categorized according to feedstock type are:

- **Dry herbaceous (examples: stover, straw, and switchgrass that are harvested at <15% moisture dry basis by weight)**
  Dry herbaceous feedstocks have been the model feedstock for work done to date to develop the feedstock infrastructure. Consequently, the dry herbaceous feedstock supply infrastructure is well-developed, and significant progress has been made toward achieving the $35/ dry ton cost target.

- **Wet herbaceous (examples: stover and switchgrass that are harvested at > 15% moisture dry basis by weight)**
  The use of wet herbaceous feedstocks is limited by a host of infrastructure barriers. As a result, wet feedstock costs are well beyond the $35/dry ton cost target. Because wet herbaceous feedstocks represent a significant portion of the overall feedstock resource, overcoming these barriers provides the greatest potential to achieve the projected tonnage targets.
- **Woody (example: logging residues)**
  Logging residues have been used for energy in Europe and the United States for nearly 30 years. As a result, the logging residue supply system is quite mature, and systems and methods are already developed to support this industry (Food and Agricultural Organization 1976; Hakkila 2004). Because near-term woody feedstock will consist largely of logging residues, the infrastructure for this feedstock can be readily adapted and validated against resource environment, resource policy, and other regional factors.
- **Energy crops (example: switchgrass)**
  With the exception of production practices, energy crops can be accommodated by dry, wet, or woody feedstock supply systems, depending on the specific type and geographic region. Thus, the energy crop supply system needs to mirror those of the dry and wet herbaceous and woody systems.

The R&D activity plan for developing and validating a feedstock supply infrastructure capable of achieving the $35/dry ton cost target for each feedstock type at the tonnages represented in Figure 4-4 above, is shown in Table 4-1. This plan outlines the necessary progress that must be supported by the feedstock R&D in order to meet the validation milestones shown for the dry (2009), woody (2011), and wet (2012) feedstock supply systems and achieve the 2012 technical target. Some of the specific intermediate feedstock R&D targets associated with this R&D plan are shown in Table 4-2. Each of these targets addresses one of three key factors—equipment capacity, equipment efficiency, or feedstock quality—affecting feedstock supply system costs. The specific research plan that focuses on the application of these cost factors to each of the supply system elements for achieving the feedstock R&D targets is described below, with a more detailed description given in Appendix D.

Table 4-1. Timeline of Key Feedstock R&D Activities to Accomplish the 2012 Technical Target

	Completion Year						
R&D Area	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Production (Grower Payment and Energy Crops)		Validate and characterize by region biomass value (i.e., grower payment)	Establish the SE, NC, W, SC, and NE Regional Partnerships	Identification, qualification and validation of feedstock for 1 and 5 B gal ethanol targets	Energy crops established and integrated by region	Site-specific residue removal parameters and constraints determined	Regional GIS-based biomass atlas for 1, 5, and 60 B gal ethanol
Feedstock Supply (Dry Biomass)	Dry biomass $35/dt analytical engineering design complete		Build, instrument, and test dry pilot scale assembly system equipment capable of validating established performance targets to meet $35/dt cost target	Dry biomass design target validated by demonstrating the achievement of all performance targets for each unit operation (pilot scale operation)			
Feedstock Supply (Wet Biomass)		Wet storage and preprocessing techno-economic assessment complete	Wet harvest, transportation, and handling techno-economic assessment complete	Wet biomass $35/dt analytical engineering design complete		Build, instrument, and test wet pilot scale assembly system equipment capable of validating established performance targets to meet $35/dt cost target	Wet biomass design target validated by demonstrating the achievement of all performance targets for each unit operation (pilot scale operation)
Feedstock Supply (Woody Biomass)			Woody biomass techno-economic assessment complete	Woody biomass $35/dt analytical engineering design complete	Build, instrument, and test woody pilot scale assembly system equipment capable of validating established performance targets to meet $35/dt cost target	Woody biomass design target validated by demonstrating the achievement of all performance targets for each unit operation (pilot scale operation)	

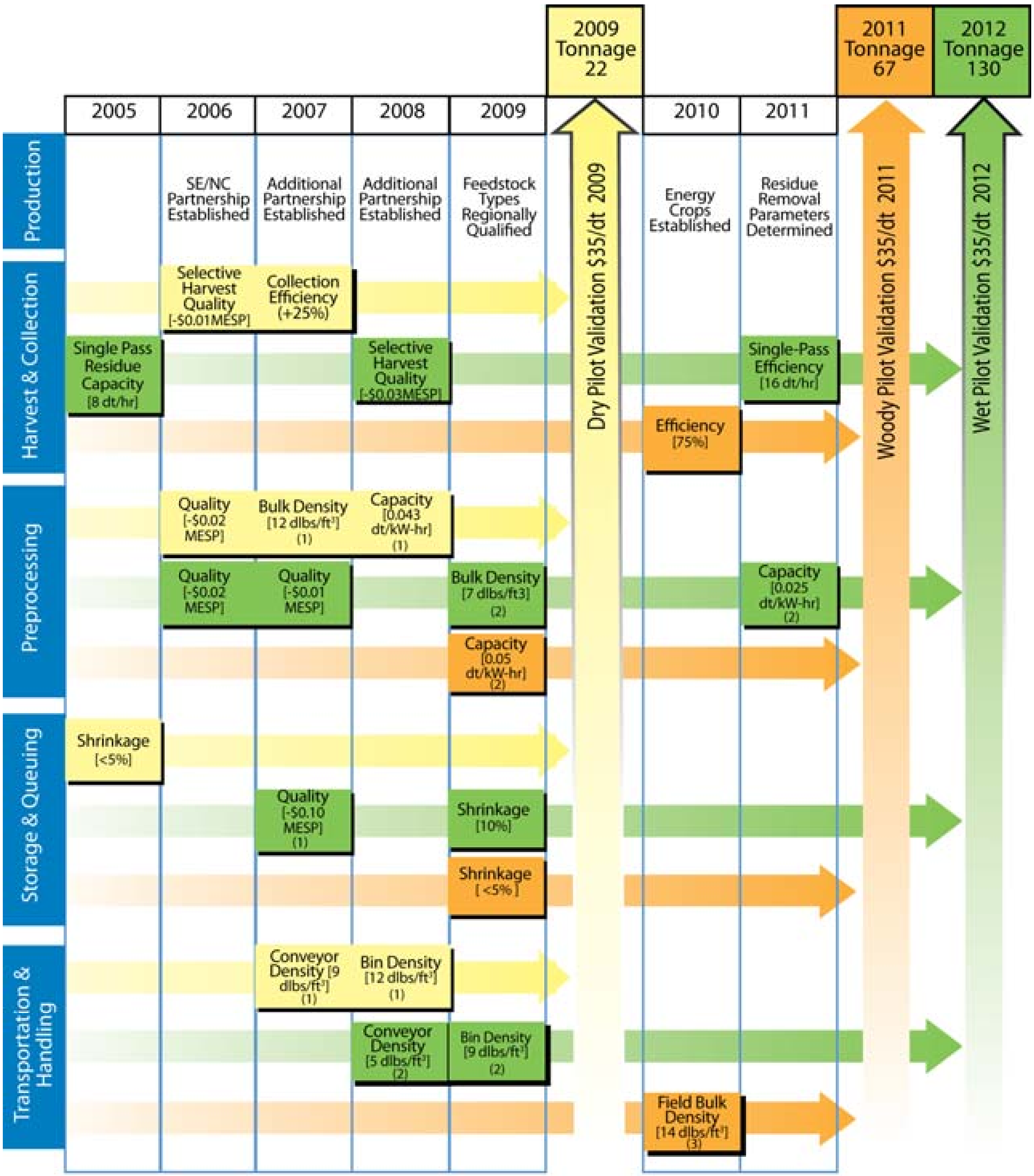
Production

Production is a critical component of the feedstock supply system, and it is key to ensuring an adequate and sustainable feedstock supply. Through USDA and regional partnership collaborations, a number of regionally based, validated assessments of production parameters—such as feedstock resource types and potentials, agronomy, crop/resource alternatives, and rotations—will be accomplished. Key milestones in this area are shown in Table 4-1.

Specific research needed to address production issues includes:

- Assessing the cost and availability of the feedstock resource on a local basis to define production costs (e.g., grower payments) and identify regional tonnages available within each feedstock type or classification at or under the feedstock threshold costs
- Identifying and validating sustainable agronomic and silvicutlure practices specific to feedstock types and regional variables to ensure sustainable production
- Investigating crop production improvements (e.g., increased yields, decreased yield variability, and consistent quality) through genetic modification
- Developing a perennial crop program that includes matching varieties to site conditions, establishing optimum agronomic and silviculture practices, and developing a seed production program.

Table 4-2. Technical Research Milestones and Validation Targets for Feedstock Cost Reductions and Increased Tonnage



(1) 15% moisture
(2) 50% moisture
(3) 20% moisture

dt = tons dry matter
dlbs = pounds dry matter

Harvest and Collection

The feedstock R&D plan depicted in Table 4-2 shows harvest and collection advances in three key areas: (1) selective harvest (including forest thinning operations), (2) single-pass or minimum-impact harvest, and (3) harvest and collection efficiencies. The primary drivers for improved harvest technologies are reduced costs and access to larger tonnages of biomass through increased producer participation. For example, improved harvest technologies that address soil quality concerns—such as carbon sequestration, nutrient/water retention, erosion, and compaction will become increasingly important for enticing grower participation and accessing biomass resources.

Performance metrics for new harvest and collection systems include (1) efficiency, (2) equipment capacity (an element of efficiency that includes technologies that reduce capital and improve throughput of equipment), and (3) quality. Without these improvements, the accessible biomass tonnage remains restricted.

Needed research in this area includes:

- Developing innovative harvest and collection methods for all resource types to eliminate or reduce unit operation costs and agronomic silviculture operational impacts
- Understanding, quantifying, and validating harvesting-specific quality related to compositional effects, pretreatment effects, contaminant reductions, and bulk handling improvements
- Developing and testing innovative equipment specific to woody feedstocks for which existing equipment is too costly and inefficient.

Pre-Processing

Significant R&D advances in dry herbaceous pre-processing have been made that will enable the transition from the current state-of-technology bale-based system to a more cost effective bulk feedstock system for biorefineries. However, as indicated in the feedstock R&D plan in Table 4-2, additional advances are needed in three key areas: (1) pre-processing equipment capacity, (2) feedstock bulk density, and (3) feedstock quality. Equipment capacity and bulk density directly affect feedstock cost. Thus, they are important technical parameters to address, along with the interrelated effect on feedstock rheological properties. Furthermore, a key component of feedstock R&D is to extend pre-processing beyond size reduction to include value-added operations that improve feedstock quality for the biorefinery. These operations involve fractionation and separation of higher-value components. These operations are necessary to achieve the feedstock cost targets embedded in the 30x30 target, both in the near- term 2012 targets as well as the long-term 2030 volume targets.
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Specific research needed in this area includes:

- Developing pre-processing requirements for each feedstock type
- Understanding the relationship between biomass structure and composition for assessing quality-upgrade potential and developing equipment and methods to achieve these upgrades

- Understanding and controlling biomass tissue deconstruction in pre-processing and the relationships among grinder configuration, tissue fractions, tissue moisture, and grinder capacity to optimize grinder configuration for fractionation, capacity, and efficiency
- Increasing bulk densities by coupling the understanding of biomass deconstruction and rheological properties with innovative bulk compaction methods
- Understanding and controlling feedstock rheological properties resulting from pre-processing operations to provide a product that minimizes problems in transportation, handling, and queuing operations.

Storage and Queuing
Feedstock shrinkage (or dry matter loss) and quality reductions are major considerations of feedstock storage. Shrinkage and quality reduction risks and mitigation strategies vary widely from region to region.

The core R&D program of DOE's Office of the Biomass Program (OBP) has demonstrated that annual dry matter loss can be as low as 0.85%, but in wetter regions, dry matter loss may exceed 25%. To achieve the 2012 cost and 30x30 supply targets, dry matter losses must be less than 5% for all feedstock types.

Specific research needed in this area includes:

- Assessing storage options and their effects on dry matter losses, compositional changes, and functional biomass changes specific to resource type and regional variables
- Establishing baselines of the costs of storage systems at scales from 0.8 million tons/year to 10 million tons/year to identify key cost and infrastructure issues and develop paths to minimize industrial-scale storage costs
- Understanding soluble sugar and carbohydrate loss and evaluating the feasibility of preventing or reclaiming those soluble sugars and carbohydrates from the feedstock during storage
- Developing cost effective methods of large-scale bulk storage that reduce handling, eliminate bulk flowability problems, and minimize adverse physical changes that may affect plant processing.

Transportation and Handling
Transportation is a significant cost and it can be a barrier to the use of some feedstock resources. Transportation and handling operations can account for nearly 50% of the capital investment of a feedstock assembly system. Unlike the other unit operations in the feedstock supply system that can impart additional value to the feedstock, transportation costs simply move the feedstock to the biorefinery. Hence reducing these costs to the minimal practically achievable is paramount to achieving the 2012 cost target and the 30x30 supply targets.

Regardless of the method of transport (e.g., truck, rail or barge), bulk density is the key technical parameter that must be addressed to decrease transportation costs. As such, methods to increase bulk density are a focus of the transportation and handling R&D. In addition, bulk handling is affected by feedstock rheological properties. This, too, is an area of focus.

Specific research needed to reduce transportation and handling costs includes:

- Understanding feedstock physical and rheological properties (including bulk density) as they relate to handling systems to optimize handling and transportation efficiencies
- Evaluating innovative transportation and handling methods.

Validation and Demonstration
As dry, wet, and woody supply system technologies are developed and the technical research targets (Table 4-2) are achieved, the supply systems will be validated to demonstrate that the resources can be supplied at the $35/dry ton cost target. This validation will be accomplished in an integrated pilot-scale facility that includes the supply system equipment and unit operations necessary to demonstrate the capacities, bulk densities, rheological properties, composition, and quality that contribute to the $35/dry ton feedstock cost for dry, wet, and woody feedstock systems.

This validation and demonstration plan is supported by single-point sensitivity analysis to relate the cost effects of technical and market parameters on the $35/dry ton feedstock cost target. (See Appendix B for a risk assessment methodology description.) The sensitivity of each unit operation identified in the feedstock roadmap (Cushman et al. 2003) for all feedstock types is shown in Figure 4-7.

This sensitivity analysis represents delivered feedstock cost ranges, where the mean value is based on the 2012 market target of $35/dry ton. The high-end cost ranges, shown in black, represent worst-case conditions and operational parameters based on the current state of technology. In the cases of storage, pre-processing, and transportation and handling, the high-end costs are directly attributed to the moisture content of the biomass at the time of each unit operation. For example, the wet storage unit operation is shown to increase the delivered feedstock cost by 55% because of 30% dry matter and function yield losses during storage and transportation. Likewise, pre-processing costs increase by 45% because of reduced capacities in grinding wet biomass, and transportation and handling costs increase by 19% because of non-productive water weight. Further, the 17% increase in harvest and collection costs comes from reduced machine efficiencies as a result of additional biomass throughput. Finally, the increase in production costs (grower payment) stems from conditions not easily controlled or mitigated by technology (such as weather, grower business practices and harvesting preferences, competing biomass markets, and transportation laws and road limits).

The cost ranges shown in blue identify potential reductions in the delivered cost of biomass feedstocks through advances in infrastructure technologies. Feedstock quality improvements account for the 15% and 17% cost reductions in storage and harvest and collection, respectively. Storage quality improvements involve capturing some of the lost sugar yield, which results from in-storage degradation. The potential cost decrease in the harvest and collection operation is a result of harvest efficiency gains and selectively harvesting (separating) the higher-sugar-content component of biomass residues from the lower-sugar-content components. These separated streams allow for a more uniform biomass feedstock, in terms of composition, which for the higher-sugar-content stream, produces more ethanol per ton of biomass and, for the lower sugar content stream, requires a less severe pretreatment. The cost reductions in pre-processing and transportation and handling, 22% and 4% respectively, are a result of improved equipment efficiencies and bulk material properties. The potential to achieve these improvements has been shown on reduced scales through laboratory and field testing results, vender specifications and equipment performance guidelines, and integrated feedstock assembly models.

A more detailed sensitivity analysis of the technical parameters that affect individual unit operations is discussed in Appendix C.

Figure 4-7. Sensitivity Analysis of Unit Operations in the Feedstock Assembly and Associated Variable Costs for All Feedstock Types

4.2 Conversion Technologies

4.2.1 Biochemical Process Technology Target for 2012

4.2.1.1 Introduction

Basically, biochemical conversion is the fermentation of sugars liberated from biomass feedstocks. The challenge is to efficiently convert the carbohydrate portion of the biomass to sugars, or "saccharify" it, and ferment the impure sugars to ethanol with a robust micro-organism. In this process the lignin component of the biomass provides the heat and power needs of the process. This process shows great promise for the cost-effective production of ethanol at high yields and with minimal environmental impact.

There are two primary routes for saccharification: (1) acid hydrolysis, either concentrated or multiple stages of dilute, and (2) pretreatment followed by enzymatic hydrolysis. In the 1980s, DOE evaluated the long-term potential of each process (Wright 1987) and although at the time acid hydrolysis technology was further developed and appeared less expensive, a comparison of progress and future potential suggested that enzymes offered greater opportunity for ethanol cost reduction in the long run (Sheehan and Riley 2001b). Acid hydrolysis technologies are certainly feasible, however, and in proper niche situations they are being pursued to commercialization.

Enzyme hydrolysis requires a pretreatment to generate an intermediate material that can be effectively digested by enzymes. Dilute acid pretreatment of corn stover followed by enzymatic hydrolysis can achieve more than 90% conversion of cellulose to glucose (Jechura 2005), compared with around 50% conversion for acid hydrolysis technologies (Zerbe and Baker 1987). Various pretreatment methods have been suggested; most use heat coupled with a chemical catalyst such as an acid, base, or other solvent. Recent advances (Decker and Selig 2006) suggest that "accessory" enzyme systems such as hemicellulases could lead to low-severity and low-cost pretreatment processes in the future. The biochemical conversion route using dilute acid as pretreatment was tentatively selected because it has strong potential and is one of the better studied options available. However, an assessment of pretreatment technologies for best applicability to meeting cost and performance goals will be performed in 2008 so that possible advancements in alternative pretreatment methods can best be accommodated.

To understand how much more development is required to meet the 2012 cost targets, DOE tracks the research state of technology by extrapolating current-year laboratory results to a conceptual process design and cost estimate. The design and cost estimates are based on engineering company consultations and ASPEN (ASPEN Plus, releases 10.1–12.1, Aspen Technology, Inc.) modeling (Aden et al. 2002). The state of technology includes only ethanol and excess electricity sales. It does not include any proprietary, company-specific enhancements over the baseline conversion technology being investigated by DOE's core biomass research program.

Figure 4-8 shows the research state of technology advances from 2001 to 2005 and reveals what is required to achieve the technical target in 2012. Most of the cost reductions from 2001 through 2005 were because of DOE-industry partnerships to reduce the cost of enzymes (Harris et al. 2006; Mitchinson 2006). As shown in Figure 4-8, the 2012 target was accelerated by DOE to accommodate the 2012 $1.07/gallon of ethanol target component of the 30x30 goal. The research outlined here addresses the R&D needs to achieve this target.

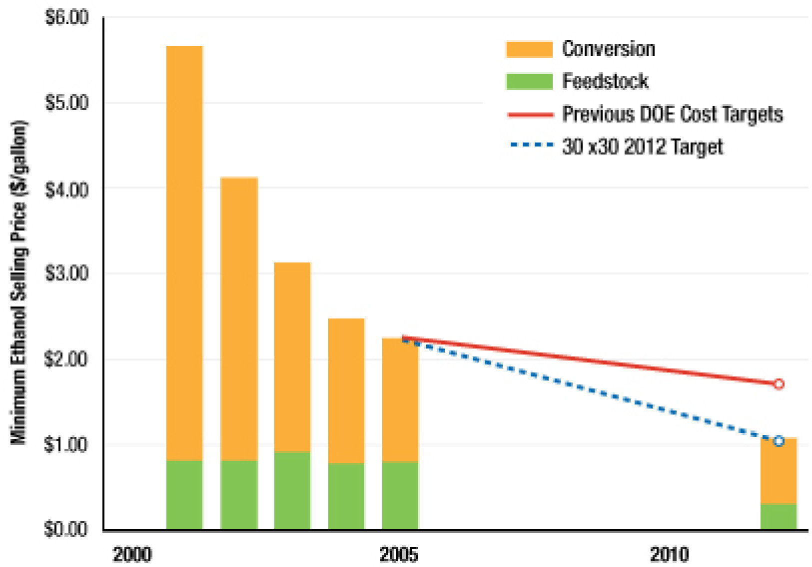


Figure 4-8. Research State of Technology for Biochemical Conversion (Foust et al. 2006)

4.2.1.2 Process Description

The biochemical conversion process selected for this scenario uses co-current dilute acid pretreatment, enzymatic saccharification, and fermentation to convert lignocellulosic feedstocks to ethanol. The process includes ancillary supporting operations such as feedstock interface handling and storage, product recovery, wastewater treatment, residue processing (lignin combustion), and product storage. See Figure 4-9.

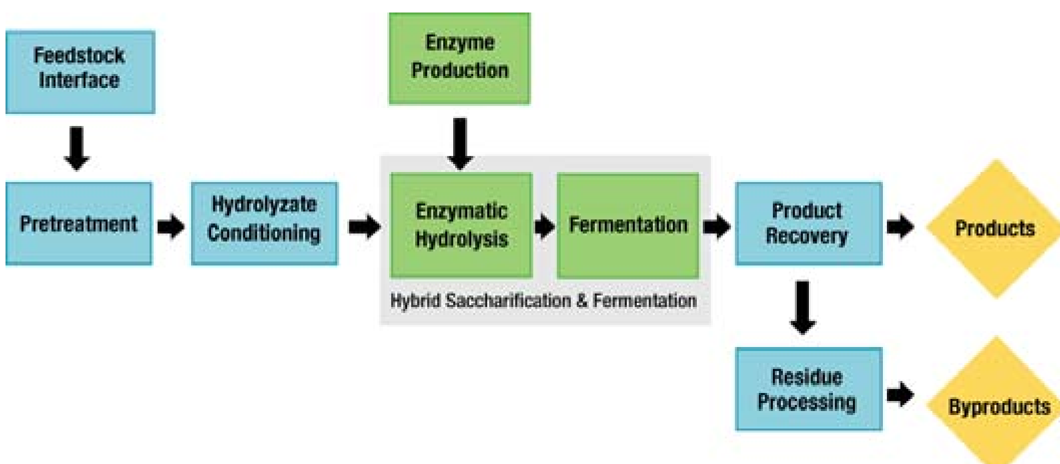


Figure 4-9. Process Schematic for Biochemical Conversion

The feedstock, initially corn stover and later other agricultural residues and energy crops, is delivered to the feed-handling area for size reduction and storage. From there, the biomass is conveyed to pretreatment and conditioning. In this area, the biomass is treated with a dilute sulfuric acid catalyst (current candidate pretreatment technology for this scenario – see Appendix D for a description of other pretreatment approaches) at a high temperature for a short time. This hydrolyzes the hemicellulose to a mixture of sugars (i.e., xylose, arabinose, galactose, mannose, and a small amount of glucose) and other compounds. In addition, the pretreatment step makes the remaining biomass more accessible for later enzyme saccharification. A conditioning process then removes byproducts from the pretreatment process that are toxic to the fermenting organism.

In hybrid saccharification and co-fermentation (HSF), the pretreated solids (now primarily cellulose) are saccharified with cellulase enzymes to form monomeric glucose. This requires a couple of days, after which the mixture of sugars and any unreacted cellulose is transferred to a fermenter. An inoculum of fermenting microorganism is added, and all sugars are fermented to ethanol. Meanwhile, the enzymes are used for further glucose production from any remaining biomass, which is now at conditions optimal to fermentation. After a few days of fermentation and continued saccharification, nearly all sugars are converted to ethanol. The resulting beer (or low-concentration ethanol) is sent to product recovery.

Product recovery involves distilling the beer to separate the ethanol from water and residual solids. An azeotrope of water and ethanol is purified to pure ethanol using vapor-phase molecular sieves. Solids from the distillation bottoms are separated and sent to the boiler (called residue processing). Distillation bottoms liquid is then concentrated by evaporation using waste heat. The evaporated condensate is returned to the process, and the concentrated syrup is sent to the burner.

Part of the evaporator condensate, along with other wastewater, is treated by anaerobic and aerobic digestion. The biogas (which is high in methane) from anaerobic digestion is sent to the burner for energy recovery. The treated water is suitable for recycle and returned to the process.

The solids from distillation, the concentrated syrup from the evaporator, and biogas from anaerobic digestion are combusted in a fluidized bed combustor to produce steam for process heat. The majority of the steam demand is in the pretreatment reactor and distillation areas. Generally, the process co-generates electricity for use in the plant and for sale to the grid.

4.2.1.3 R&D Needs To Achieve the 2012 Technical Target

The R&D required to meet the 2012 technical target is outlined in Table 4-2. It is important to note that technology advancement must be verified at the pilot scale as well as at the laboratory bench scale. By 2012, the technology, and subsequently the data for calculating costs, will be generated from integrated pilot plant runs.

Accomplishing the 2012 goal requires additional technology advancement in key areas of the dilute acid and enzymatic hydrolysis process (Foust et al. 2006).

Figure 4-10 shows the technical barrier areas that must be addressed by R&D for the individual unit operations to meet the 2012 target. Table 4-3 provides quantitative targets that must be achieved at various stages of the development process to achieve the cost target of $1.07/gallon by - 2012 target. As stated earlier, this process scenario is specific to dilute acid pretreatment, for a description of possible contributions of other pretreatment technologies and contingency plans, see Appendix D. The following sections will describe the R&D approach to meeting the targets by the dates specified in Table 4-3

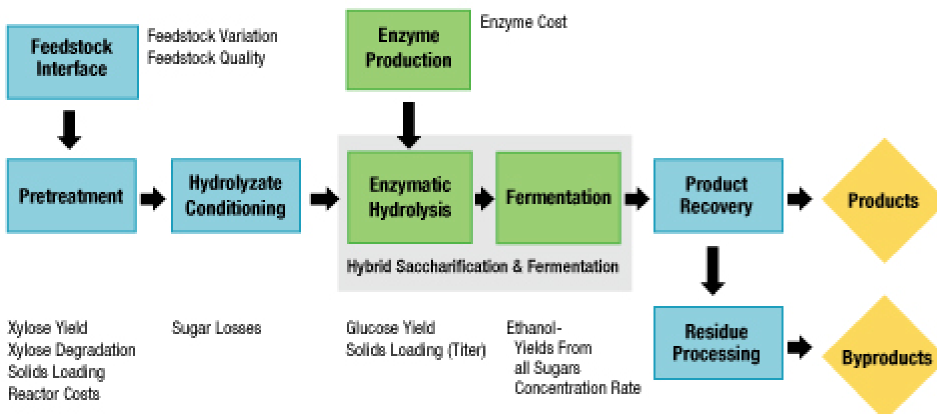


Figure 4-10. Process Flow Diagram Highlighting Major Research Barriers

Table 4-3. Timeline of Key Activities to Accomplish the 2012 Technical Target

	Completion Year					
R&D Area	**Current**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Feedstock Interface	Corn stover	Determine which feedstock types will be used in pioneer plants and have the potential to provide significant volumes (>100 million tons/year)	Develop/adapt dry corn stover analytical methods for diverse samples (>3) of another feedstock type (e.g. switchgrass) achieving mass balance closure of 100% ± 5%	Define the relationships between variations in the feedstock composition and key processing parameters	Develop/adapt dry corn stover analytical methods for diverse samples (>3) of another feedstock type (e.g. ensiled corn stover) achieving mass balance closure of 100% ± 5%	Define the relationships between variations in the feedstock composition and key processing parameters	Develop cost correlations for two other feedstocks based on the corn stover $1.07/gal baseline
Pretreatment	63% xylan yields and 13% sugar degradation in continuous reactor with > 30% solids from corn stover	1) Achieve 75% xylose yield in laboratory scale high solids pretreatment reactor on corn stem internode 2) Define the relationships between pretreatment conditions and the chemical/ultrastructural changes in corn stover stems that result in biphasic xylan hydrolysis	Validate > 75% xylan yield & < 8% degradation from corn stover using a continuous reactor	1) Understand sugar degradation kinetics & how to reduce degradation to < 6% for corn stover 2) Test accessory enzymes' effect on reducing pretreatment costs for corn stover in lab equipment	1) Achieve > 85% xylan yields and < 6% sugar degradation from corn stover using a continuous reactor with > 30% solids 2) Make final decision on pretreatment process to use in 2012 pilot operation	Provide bench scale pretreatment data on two other feedstocks (e.g. switchgrass, ensiled corn stover) to develop cost correlations against the corn stover baseline	Achieve >90% xylan to xylose & < 5% xylan degradation from corn stover in integrated pilot operation with > 30% solids
Hydrolyzate Conditioning	13% sugar losses in overliming conditioning step on corn stover		Define the relationships between corn stover hydrolyzate conditioning and fermentation performance in lab equipment	Reduce sugar losses in corn stover hydrolyzate conditioning step to < 7% in laboratory equipment (accessory enzymes is one option)	Reduce sugar losses in corn stover hydrolyzate conditioning step to < 2% in laboratory equipment	Provide bench scale conditioning data on two other feedstocks (e.g. switchgrass, ensiled corn stover) to develop cost correlations against the corn stover baseline	Reduce sugar losses in corn stover hydrolyzate conditioning step to < 1% in integrated pilot operation or eliminate need for conditioning

Enzyme Production	$0.32/gallon of ethanol	Develop the first generation computational model of CBH I capable of describing structure and function, and verify CBH I structure	1) Baseline commercial cellulases' specific activity 2) Determine how cellulase enzymes move along cellulose chains	Conduct targeted substitutions of cellobiohydrolase to increase specific activity by 2-fold relative to native	1) Define cellulase interactions at the plant cell wall 2) Validate the cost contribution of purchased enzyme at $0.16/gal EtOH	Validate the cost contribution of purchased enzyme at $0.10/gal EtOH	Validate a $0.10/gal cost contribution of purchased enzyme used in integrated pilot operation
Enzymatic Saccharification and Fermentation	> 85% Cellulose to EtOH, > 75% xylose to EtOH, 0% other sugars to EtOH in a total of 7 days in lab equipment with > 20% total solids from corn stover		Demonstrate > 85% cellulose to EtOH, > 80% xylose to EtOH, > 40% other sugars to EtOH in a total of 7 days in lab equipment with > 20% total solids	Define the relationships between lignin redeposition and enzyme kinetics	Demonstrate > 85% cellulose to EtOH, > 80% non-glucose sugar to EtOH in a total of 5 days in lab equipment with > 20% total solids	1) Demonstrate > 85% cellulose to EtOH, > 85% non-glucose sugar to EtOH in a total of 3 days in lab equipment with > 20% total solids 2) Develop bench scale SSF data on two other feedstocks (switchgrass, ensiled corn stover) to develop cost correlations against the corn stover baseline	Demonstrate > 85% cellulose to EtOH, > 85% non-glucose sugar to EtOH in a total of 3 days in integrated pilot operation with > 20% total solids
Integration/Modeling	Research state-of-technology utilizing current data and modeling shows a $2.26/gal ethanol selling price with total capital of $3.04/gal of annual installed capacity for corn stover		Complete rapid analysis method to predict component concentrations in pretreated slurry stream to same accuracy as wet chemistry methods	Completed biochemical pilot facility with 2 or more pretreatment trains and occupancy formally handed over to operating entity	1) Biochemical pilot facility shakedown completed (For NREL, demonstrated by successful operation of new pretreatment train(s) on corn stover) 2) Process cost estimate updated with latest data and engineering consultations	Provide equipment and operating costs for the corn stover $1.07/gal baseline to develop cost correlations for 2 other feedstocks	Data from integrated pilot operation combined with process design & cost estimate validates a $1.07/gal ethanol selling price and capital cost of $1.85/gal of annual installed capacity for nth plant (adjusted to the current cost year from 2000$) for corn stover

Feedstock/Process Interface R&D Needs
The feedstock/process interface targets are to:

- Determine the sensitivity of the overall process to differences in feedstock type and quality
- Determine how to adjust and modify the process to accommodate changes in feedstock.

The research goals are to:

- Understand the range of feedstock types expected to be used in pioneer plants
- Work with feedstock suppliers and researchers to improve the quality (physical and chemical characteristics) of the feedstocks
- Determine the impacts of the feedstocks on downstream unit operations
- Understand how to adjust the process to maintain optimal yields and productivities with varying feedstock quality or different feedstocks.

Pretreatment and Hydrolyzate Conditioning R&D Needs
The first pretreatment and hydrolyzate conditioning target is to increase the xylan-to-xylose conversion to 90% while reducing the xylan lost to degradation products to 5% and maintaining or increasing the solids loading of 30% in a continuous pilot-scale reactor.

The research goals are to:

- Determine the location of the xylan in the plant cell wall and optimize pretreatments that selectively remove and hydrolyze it to xylose
- Reduce sugar degradation to minimal levels by understanding the kinetic mechanisms that lead to undesirable degradation products and then systematically blocking these pathways
- Down-Select one primary pretreatment technology for further development.

The second target is to reduce the capital cost of pretreatment through the use of ancillary enzymes. The research goal here is to determine if other enzymes, such as xylanases, can improve xylose yields, minimize the formation of degradation products, reduce costs associated with the pretreatment process by reducing severity, and reduce the need for conditioning.

The final target is to eliminate or greatly reduce the need for conditioning.

The research goals are to:

- Understand the role of hydrolyzate conditioning to eliminate sugar losses

- Understand and control the degradation kinetics to minimize or eliminate the formation of inhibitory compounds.

Enzyme Production R&D Needs
The enzyme production target is to reduce purchased enzyme cost to $0.10/gallon of ethanol produced for a 90% conversion of cellulose to glucose within 3 days in an HSF system.

The research goals are to:

- Understand cellulase interactions at the plant cell wall ultrastructural level to optimize hydrolysis processes, enzyme kinetics, and, ultimately, cellulase use and cost
- Determine how cellulase enzymes move along the cellulose chain and the roles of enzyme substructures
- Conduct targeted substitutions of enzyme components to increase specific activity guided by molecular modeling of cellulase/substrate interactions
- Identify enzyme production processes and logistics to minimize processing and transportation costs of enzyme products.

Enzymatic Saccharification and Fermentation R&D Needs
The first enzymatic saccharification and fermentation target is to develop a robust, commercially viable biocatalyst (or micro-organism) capable of fermenting 85% of hemicellulose sugars and 95% of glucose to a concentration of at least 6% ethanol in three days in combined hybrid saccharification and fermentation.

The research goals are to:

- Identify strain candidates that exhibit superior "wildtype" performance
- Use metabolomics, proteomics, and other tools to understand metabolic bottlenecks in the carbon assimilation pathways that limit pentose sugar uptake and the ability to withstand fermentation inhibitors such as organic acids, low pH, and increased temperature
- Extend "omics" studies to identify and understand secondary pathway limitations related to reaction cofactors and regulation of metabolism
- Increase pentose uptake rates by applying protein and metabolic engineering to increase sugar transporter efficiency, pentose specificity, and expression
- Improve strain robustness by manipulating cell membrane composition to reduce its permeability to organic acids and improve its temperature stability
- Use a combination of metabolic engineering, mutagenesis, and long-term culture adaptation strains on actual pretreatment hydrolyzate to achieve targeted fermentation performance
- Perform parametric analysis of such factors as lignin redeposition and the detrimental effects this can have on enzyme kinetics to minimize these effects.

The second target is to develop an HSF process capable of saccharifying 90% of cellulose to glucose and fermenting 85% of hemicellulose sugars and 95% of glucose to ethanol in three days while maintaining the solids concentration necessary for the ethanol concentration target above.

The research goals are to:

- Use information about the enzyme capabilities and fermenting strain's performance to develop and test strategies for efficiently integrating enzymatic hydrolysis with biomass sugar fermentation to maximize cellulose hydrolysis and sugar fermentation rates and yields
- Quantify the effects of enzyme loading, strain inoculation time, and inoculum charge on batch process performance
- Use reactor designs and operational schemes to maximize the solids loading and conversion of cellulose and other sugars to ethanol.

Integration/Process Engineering R&D Needs

The integration/process engineering targets are to:

- Optimize key unit operations, pretreatment, hybrid saccharification and fermentation, product recovery, and residue processing (separations only) in an integrated pilot plant with appropriate recycles
- Obtain the data necessary to update the process design and cost estimate to validate the 2012 technical target.

The research goals are to:

- Set up all unit operations in a safe, integrated system capable of continuous operation — 24 hours per day, 7 days per week — with data-gathering capabilities
- Develop analytical methods and equipment to monitor the process and collect data
- Test the integrated process and optimize conditions to maximize performance
- Use data from the operating pilot plant to complete a conceptual full-scale process design and cost estimate to validate the 2012 technical target.

As shown, reaching the 2012 technical target for biomass conversion requires a specific set of research targets. As outlined in Table 4-2 missing any one of these targets would mean missing the 2012 target. However, other combinations of research results could result in achieving the 2012 technical target of $1.07/gallon ethanol. Hence continuous rigorous R&D progress tracking with appropriate contingency plans coupled with risk assessment needs to be a critical component of implementing this research plan (Appendix E).

In addition, there is more sensitivity (a larger benefit if exceeded or a bigger detriment if not met) to some research activities than others. A set of ethanol selling prices were calculated using variations of research targets to understand the effect of missing or exceeding targets. These variations are based on the judgment of researchers in the field. In some cases, the low value is what has been accomplished. Figure 4-11 illustrates the effect on calculated selling price of a range of research results and parameters. The figure includes only the targets that exhibit a sensitivity range greater than \$0.10/gallon. (See Appendix E for additional sensitivities.) The figure illustrates that:

- Some targets will have significant effects on the final outcome
- If some targets are exceeded and others are missed, the final target selling price of \$1.07/gallon can still be achieved.

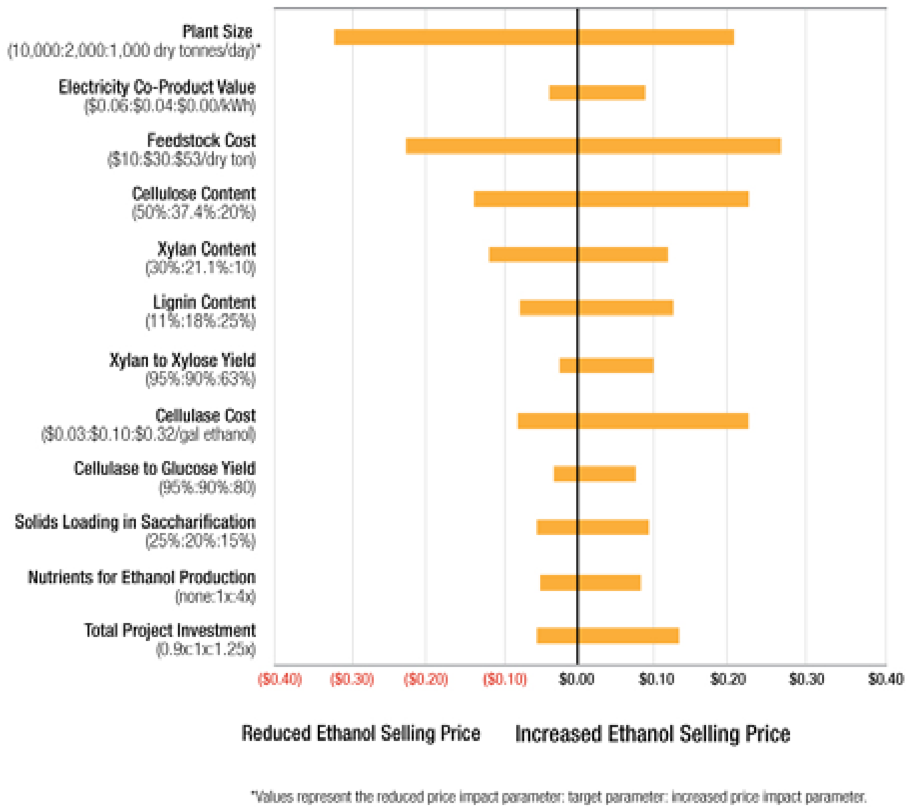


Figure 4-11. Research Outcomes and Variables with Potentially Large Effects on the 2012 Technical Target

4.2.2 Thermochemical Process Technology Target for 2012

4.2.2.1 Introduction

Thermochemical conversion technology options include gasification and pyrolysis. Although both routes show considerable long-term promise, gasification is more suitable for alcohol fuels production and shows considerable near-term promise for economic competitiveness. Therefore, gasification is the chosen thermochemical conversion route to meet the 2012 technology target. As stated in Section 4.2, the thermochemical process to alcohol fuels adds technology robustness to this 30x30 scenario in converting the required portion of the feedstock based to ethanol in that it can more easily convert low-carbohydrate, or “non-fermentable,” biomass materials such as forest and wood residues to alcohol fuels than the biochemical conversion process route. This section describes the R&D needed to achieve the

2012 market target production price for a standalone biomass gasification/ mixed alcohol process.

In the long-term advanced technology scenarios rely on yield enhancements achieved by combining biochemical and thermochemical conversion technologies in an integrated biorefinery. Integrated biorefineries will thermochemically convert lignin-rich bioconversion residues into biofuel to maximize the liquid fuel yield per delivered ton of biomass. Once the technology has been proven in a standalone manner and the biochemical facilities become large enough to provide sufficient feed, integrated biochemical and thermochemical facilities will be possible.

Biomass gasification converts heterogeneous feedstock supplies into a consistent gaseous intermediate that can be converted to liquid fuels. The product gas (called "synthesis gas" or "syngas") has a low to medium energy content (depending on the gasifying agent) and consists mainly of carbon monoxide, hydrogen, carbon dioxide, water, nitrogen, and hydrocarbons. Minor components, also referred to as contaminants, include tars, sulfur and nitrogen oxides, alkali metals, and particulates. These contaminants threaten the success of downstream syngas to liquid fuels conversion and must either be reformed or removed. For this scenario an indirect gasification technology is used (Spath et al. 2005) predominantly because of the lower capital cost of indirect gasification compared to direct gasifier technology (Appendix F).

Commercially available and near-commercial syngas conversion processes were evaluated on technological, environmental, and economic bases by Spath and Dayton (Spath and Dayton 2003). Their report provides the basis for identifying promising, cost-effective fuel synthesis technologies that maximize the impact of biomass gasification. For the purpose of this scenario, a pre-commercial, mixed-alcohols synthesis process that implements an alkali-promoted molybdenum disulfide catalyst, a variant of Fischer-Tropsch synthesis, was selected as the technology of choice because high yields of ethanol are possible with targeted R&D advancements. The sulfided molybdenum catalyst is also tolerant of low levels of sulfur gases, which are common catalyst poisons. Appendix F contains a detailed evaluation of other mixed-alcohol synthesis catalyst options.

Conceptual designs and techno-economic models were developed for a standalone biomass gasification process with thermochemical ethanol production via mixed-alcohols synthesis. The models were developed to determine how overcoming technical barriers could contribute to reductions in finished ethanol costs (Aden and Spath 2005). For example, the proposed mixed-alcohol process does not produce ethanol with 100% selectivity. The production of higher normal alcohols (e.g., n-propanol, n-butanol, and n-pentanol) is unavoidable. Fortunately, the byproduct higher alcohols have value as commodity chemicals and fuel additives as well as mixed-alcohols fuels. Therefore, two thermochemical ethanol scenarios and their economic ramifications were considered.

1. Separating the higher alcohols from the mixed-alcohol product and selling them at a percentage of their chemical market value
2. Selling the unseparated mixed-alcohol stream as fuel at a btu adjusted basis with ethanol.

Both scenarios achieve the $1.07/gallon (2002 dollars) (Jechura, Thermochemical Design Report, 2007) market target. However, the case with the higher alcohols separated and sold into their respective markets provides the initial economic benefit to accelerate deployment of these thermochemical technologies by making the first plants economically more attractive.

The conceptual process design and ethanol production cost estimate quantify the benefits of meeting R&D goals for tar reforming and improved mixed-alcohol catalyst performance, as shown in Figure 4-12. The current case design defines today's R&D state of technology, particularly with regard to removal/conversion of tars and literature data for mixed-alcohol synthesis catalyst performance. The schedule for improved tar reforming and mixed-alcohol synthesis catalyst performance was accelerated by the 30x30 scenario to achieve $1.07/gallon thermochemical ethanol by 2012.

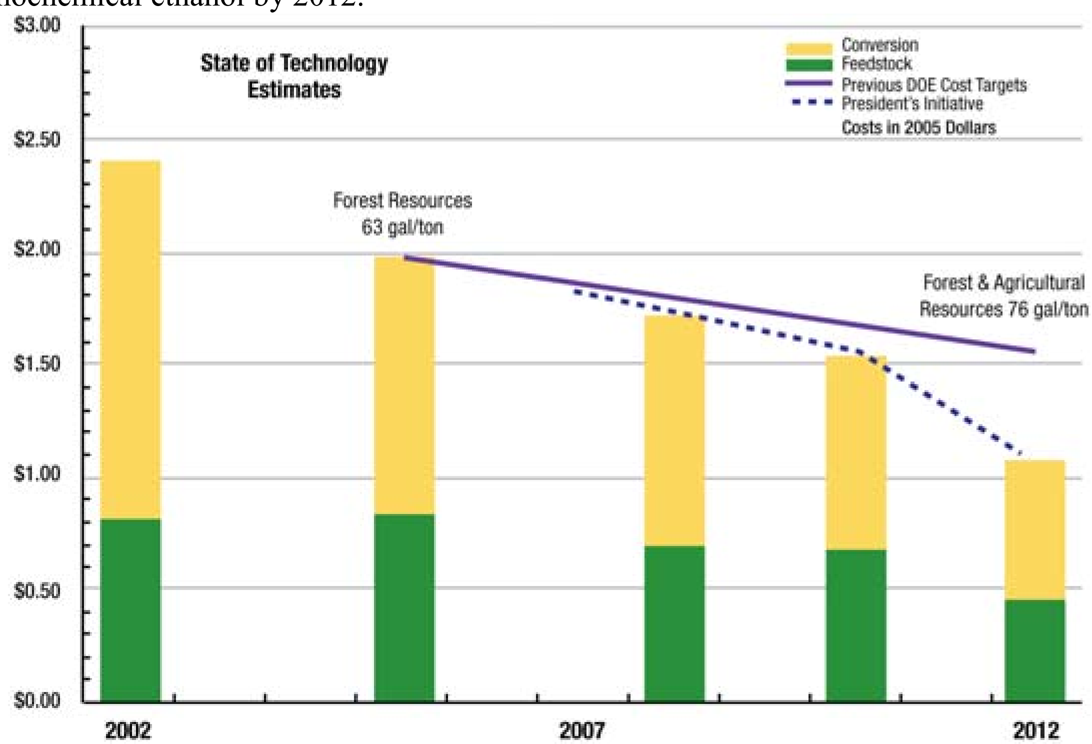


Figure 4-12. Research State-of-Technology Assessments for Thermochemical Ethanol Production to Reach the $1.07/Gallon Market Target (Foust et al. 2006)

4.2.2.2 Process Description

Figure 4-13 shows a block process flow diagram of the thermochemical process necessary to reach the $1.07/gallon market target and major technical barriers to the target case. The feedstock interface addresses the main biomass properties that affect the long-term technical and economic success of a thermochemical conversion process: moisture content, fixed carbon and volatiles content, impurity concentrations, and ash content. High moisture and ash content reduce the usable fraction of delivered biomass. Therefore, maximum system efficiencies are possible with dry, low-ash biomass.

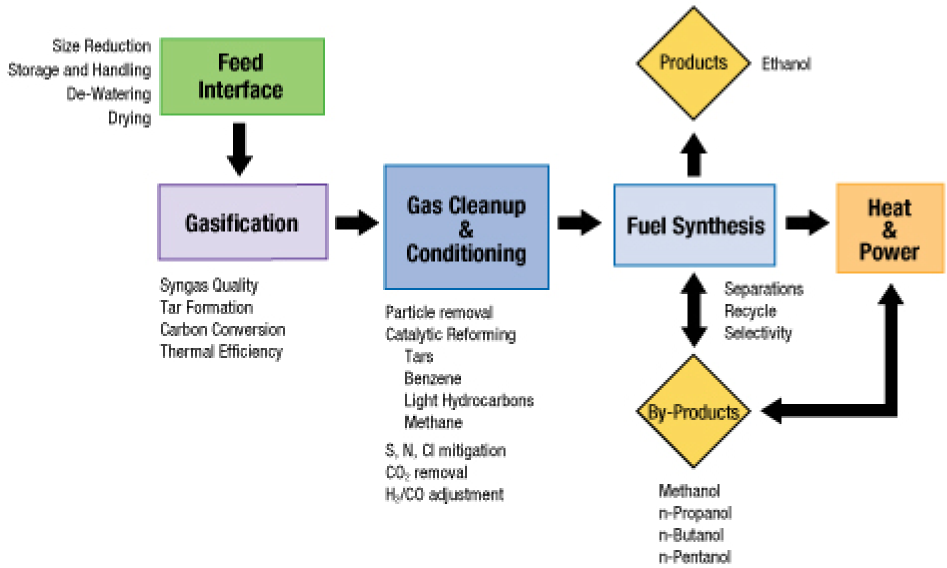


Figure 4-13. Process Flow Diagram with Research Barriers for Thermochemical Ethanol Production at $1.07/Gallon

Biomass gasification is a complex thermochemical process that begins with the thermal decomposition of a lignocellulosic fuel. This is followed by partial oxidation of the fuel with a gasifying agent—usually air, oxygen, or steam—to yield raw syngas. The raw gas composition and quality are dependent on a range of factors, including feedstock composition, type of gasification reactor, gasification agents, stoichiometry, temperature, pressure, and the presence or lack of catalysts.

Gas cleanup is the removal of contaminants from biomass gasification product gas. It generally involves an integrated, multi-step approach, which varies depending on the intended end use of the product gas. However, gas cleanup normally entails removing or reforming tars and acid gas, ammonia scrubbing, capturing alkali metal, and removing particulates. Gas conditioning is the final modification to gas composition to make it suitable for a fuel synthesis process. Typical gas conditioning steps include sulfur polishing (to reduce levels of hydrogen sulfide to acceptable amounts for fuel synthesis) and water-gas shift (to adjust the final hydrogen-carbon monoxide ratio for optimized fuel synthesis).

Comprehensive cleanup and conditioning of the raw biomass gasification product gas yields a "clean" syngas composed of carbon monoxide and hydrogen, in a given ratio. This gas can be converted to a mixed-alcohol product. The separation of ethanol from this product yields a methanol-rich stream that can be recycled with unconverted syngas to improve process yield.

The higher-alcohol-rich stream yields byproduct chemical alcohols. The fuel synthesis step is exothermic, so heat recovery is essential to maximize process efficiency.

4.2.2.3 R&D Needs To Achieve the 2012 Technical Target

The 2007–2012 R&D activities essential to overcoming technical barriers and meeting the 2012 technical target for thermochemical ethanol production are outlined in Table 4-4. These activities include fundamental kinetic measurements, micro-activity catalyst testing, bench-scale thermochemical conversion studies, pilot-scale validation of tar-reforming catalyst performance, and pilot-scale demonstration of integrated biomass gasification mixed-alcohol synthesis. Process data collected in integrated pilot-scale testing will provide the basis for process optimization and cost estimates to guide technology deployment.

Feedstock/Process Interface R&D Needs

Because the 30x30 scenario envisions mixed-alcohol conversion of low-grade or “non-fermentable” feedstocks, refinements in dry biomass feeder systems will be required to meet cost targets. These refinements should reduce up front feed-processing requirements to yield biomass feedstocks at $35/ton at less than 15% moisture (dry basis) by weight delivered to the gasifier. Additional challenges that will be associated with feeding the biomass into pressurized biomass gasification systems are discussed in Appendix F.

Gasification Studies R&D Needs

The thermochemical mixed-alcohol synthesis conversion route is envisioned initially for forest resources and other low-carbohydrate feedstocks and residues. Hence, gasification studies will need to determine how feedstock composition affects syngas composition, quality, and efficiency. The gasifier technology chosen for this analysis is the Battelle Columbus Laboratory indirectly heated gasifier; however, other gasifier technologies could prove more promising (see Appendix F). These technologies must be tracked to ascertain their applicability to the mixed-alcohol synthesis process.

Cleanup and Conditioning R&D Needs

Techno-economic analysis (Aden and Spath 2005) has shown that removing chemical contaminants such as tar, ammonia, chlorine, sulfur, alkali metals, and particulates has the greatest effect on the cost reduction of mixed-alcohol synthesis. To date, gas cleanup and conditioning technologies are unproven in integrated biorefinery applications. The goal is to eliminate tar removal and disposal via water quench, which is problematic from efficiency and waste disposal perspectives, and develop a consolidated tar and light hydrocarbon reforming case.

Current laboratory-scale demonstration results and target conversions for impurities in biomass-derived syngas are listed in Table 4-3. The goal conversions were selected to yield an economically viable, clean syngas suitable for a catalytic fuel synthesis process without further hydrocarbon conversion steps.

Table 4-4. Thermochemical Ethanol (Gasification/Mixed Alcohols) R&D Targets

R&D Area	Current	2007	2008	2009	2010	2011	2012
Feedstock Interface	\$30/dry ton wood chips 50% moisture dried to 12% - 2000 tpd plant					\$30/dry ton biorefinery residues based on \$45/dry ton corn stover. 50% moisture dried to 12% - 2000 tpd plant	
Thermochemical Conversion - Gasification	Wood chips (model) - Indirect (atm) gasification – 78% syngas efficiency: H_2/CO = 1.0-1.5 CH_4≤15vol% Tars ≤30 g/Nm^3 benzene ≤ 1vol% H_2S = 50-600 ppm NH_3 and HCl to be determined	Biorefinery residues - Indirect (atm) gasification : corn stover; switchgrass; wheat straw; lignin - 78% syngas efficiency: H_2/CO = 1.0-1.5 CH_4≤15vol% Tars ≤30 g/Nm^3; benzene ≤ 1vol% H_2S = 50-600 ppm NH_3 and HCl to be determined	Demonstrate biomass gasification for \$6.88/MMBtu syngas cost based on 2007	Indirect (atm) gasification –78% syngas efficiency: H_2/CO = 1.0-1.5 CH_4≤8vol% Tars ≤10 g/Nm^3; benzene ≤ 0.1vol%; H_2S ≤ 20 ppm; NH_3 and HCl to be determined	Demonstrate biomass gasification for \$5.25/MMBtu syngas cost	Indirect (atm) catalytic gasification – 78% syngas efficiency: H_2/CO = 1.0 CH_4 ≤ 5vol% Tars ≤ 1 g/Nm^3; benzene ≤ 0.04 vol%; H_2S ≤ 20 ppm; NH_3 and HCl to be determined	
Cleanup and Conditioning	Cyclone particulate removal H_2S ≥ 50 ppm (based on feedstock) with no S removal Tar Reformer Efficiency CH_4 ≥20% Benzene ≥70% heavy tars ≥95% (79% CH_4 conversion in separate SMR)	Sorbent injection to maintain H_2S levels ≤ 50 ppm for syngas from biomass to reduce sulfur deactivation of tar reforming catalysts.	Tar Reformer Efficiency CH_4 ≥50% Benzene ≥90% heavy tars ≥97% (79% CH_4 conversion in separate SMR)	Improve tar reforming catalyst performance - Regen/TOS ratio ≤ 600	Tar Reformer Efficiency CH_4 ≥80% Benzene ≥99% heavy tars ≥99.9% Eliminate SMR; highest activity re-gained by regenerating deactivated catalyst	Improve tar reforming catalyst performance - Regen/TOS ratio ≤ 250	Integrated operations for syngas cleanup and conditioning target composition for fuel; synthesis: CH_4 ≤3vol% Benzene ≤10 ppm Heavy tars ≤0.1 g/Nm^3 H_2S ≤1 ppm NH_3 ≤ 10 ppm HCl ≤ 10 ppb
Catalytic Fuels Synthesis (Mixed Alcohols)	H_2/CO = 1.2 Pressure ≤ 2000 psia Productivity = 100-400 gMA/kg(cat)/hr EtOH Selectivity ≥70% (CO_2-free)	H_2/CO ≤ 1.2 Pressure ≤ 2000 psia Productivity ≥ 150 gMA/kg(cat)/hr EtOH Selectivity ≥70% (CO_2-free)	Demonstrate 500 hours catalyst lifetime at 2007 performance with bottled syngas for mixed alcohol catalyst cost of ≤ \$0.50/gal EtOH	H_2/CO ≤ 1.0 Pressure ≤ 1500 psia Productivity ≥ 300 gMA/kg(cat)/hr EtOH Selectivity ≥75% (CO_2-free)	Demonstrate 500 hours catalyst lifetime at 2009 performance. with biomass syngas for mixed alcohol catalyst cost of ≤ \$0.22/gal EtOH	H_2/CO ≤ 1.0 Pressure ≤ 1000 psia Productivity ≥ 600 gMA/kg(cat)/hr EtOH Selectivity ≥80% (CO_2-free)	Demonstrate 1000 hours catalyst lifetime at 2009 performance. with biomass syngas
Integration and Modeling	Research state-of-technology - 56 gal/dry ton EtOH \$2.02/gal minimum EtOH selling price (higher alcohols sold at 85% of market value) at \$2.71/gal installed capital costs.	<u>Biomass Gasification/Mixed Alcohol Design Report</u> - Establishes a cost and quality baseline for technology improvements for \$1.07/gal thermochemical ethanol by 2012 from indirect biomass gasification through a clean syngas intermediate.	Improved hydrocarbon conversion efficiency yields- 56 gal/dry ton EtOH \$1.73/gal minimum EtOH selling price (higher alcohols priced as gasoline on an energy adjusted basis - \$1.15/gal) at \$2.69/gal installed capital costs.	Validated \$1.73/gal EtOH for integrated Cleanup & Conditioning + Mixed Alcohol synthesis	Demonstrate feasibility of system (8000 hr on stream with ≤10% catalyst losses per year) based on regenerating fluidizable tar reforming catalyst to eliminate SMR	Validated \$1.35/gal EtOH for integrated Cleanup & Condtioning + Mixed Alcohol synthesis	Demonstrate mixed alcohol yields of 89 gal/ton (76 gal/dry ton EtOH) via indirect biomass gasification at pilot-scale for “\$1.07” minimum ETOH selling price (higher alcohols priced as gasoline on an energy adjusted basis - \$1.15/gal). Total installed capital costs are \$2.31/annual gallon of ethanol.

The research target will be met when tar and light hydrocarbons are sufficiently converted to additional syngas to technically validate the elimination of an additional steam methane-reforming unit operation. Specific research needed for the design and demonstration of a regenerating tar-reforming reactor for long-term, reliable gas cleanup and conditioning includes:

- Performing tar deactivation/regeneration cycle tests to determine activity profiles to maintain the required long-term tar-reforming catalyst activity
- Performing catalyst studies to determine deactivation kinetics and mechanisms by probing catalyst surfaces to uncover molecular-level details
- Determining optimized catalyst formulations and materials at the pilot scale to demonstrate catalyst performance and lifetime as a function of process conditions and feedstock.

Although consolidated tar and light hydrocarbon reforming tests performed with nickel-based catalysts have demonstrated the technical feasibility of this strategy, alternative catalyst formulations can optimize reforming catalyst activity, lifetime, and functionality. Specific research needed to realize improvements in catalyst functionality include:

- Designing catalysts with higher tolerances for sulfur and chlorine poisons to enable further process intensification
- Lowering or eliminating the sulfur and chlorine removal cost prior to reforming to achieve further reductions in gas cleanup costs
- Optimizing the water gas shift activity of reforming catalysts to reduce or eliminate the need for an additional downstream shift reactor.

Catalytic Fuels (Mixed-Alcohol) Synthesis R&D Needs

The commercial success of mixed-alcohol synthesis has been limited by poor selectivity and low product yields. Single-pass yields are on the order of 10% syngas conversion (38.5% carbon monoxide conversion) to alcohols, with methanol typically being the most abundant alcohol produced (Wender 1996; Herman 2000). For mixed-alcohol synthesis to become an economical commercial process, improved catalysts are needed (Fierro 1993). Improvements in mixed-alcohol synthesis catalysts could increase alcohol yields and the selectivity of ethanol production from clean syngas, as well as improve the overall economics of the process through better heat integration and control and fewer syngas recycling loops.

Specific research needed to achieve the $1.07/gallon 2012 market target case includes:

- Developing improved mixed-alcohol catalysts that increase the single-pass carbon monoxide conversion from 38.5% - 50% (and potentially higher) and improve the carbon monoxide selectivity to alcohols from 80% - 90%
- Developing improved mixed-alcohol catalysts with higher activity that require a lower operating pressure (1,000 psia compared with 2,000 psia) to decrease process operating costs. (The combination of lower syngas pressure for alcohol synthesis and less

unconverted syngas to recompress and recycle has the added benefit of lowering the energy requirement for the improved synthesis loop.)

- Exploring alternative mixed-alcohol synthesis reactors and catalysts. (Greatly improved temperature control of the exothermic synthesis reaction has been demonstrated to improve yields and product selectivity. Precise temperature control reactor designs need to be developed for the mixed-alcohol synthesis reaction to improve the yields and economics of the process.)

Integration/Demonstration Needs
For any sophisticated conversion process, combining individual unit operations into a complete, integrated, systematic process is a challenge. To demonstrate the $1.07/gallon technology, individual pilot-scale operations and complete, integrated pilot development runs will be required. A specific challenge is to continue to demonstrate process intensification and higher yields at pilot scale to reduce capital costs.

Achieving the technical target for the accelerated path to thermochemical ethanol requires meeting the research targets outlined above. Missing or delaying any of these targets forfeits the 2012 target and jeopardizes technology deployment to meet the 30x30 goal. The cost implications of missing, hitting, or exceeding a target or set of targets are determined with process uncertainty analysis. Figure 4-14 shows the results of a single-point uncertainty analysis based on 2012 thermochemical ethanol technology. The uncertainties in the figure show the range of ethanol costs around the $1.07/gallon target.

Figure 4-14 does not provide an exhaustive list of uncertainties but rather focuses on those thought a priori to have the greatest effects. The market and financial uncertainties examined here are essentially the same as those explored for the biochemical process. The analysis shows that the effect of certain process variables is less than expected (e.g., the relatively small effect of reforming catalyst lifetime).

Combinations of sensitivity analyses can reveal several ways to achieve the same $1.07/gallon cost target, which reduces the overall risk of the process. Quantifying the relative cost savings for process improvements allows work to be directed to the most cost-effective R&D to achieve the 2012 technical target for thermochemical ethanol production.

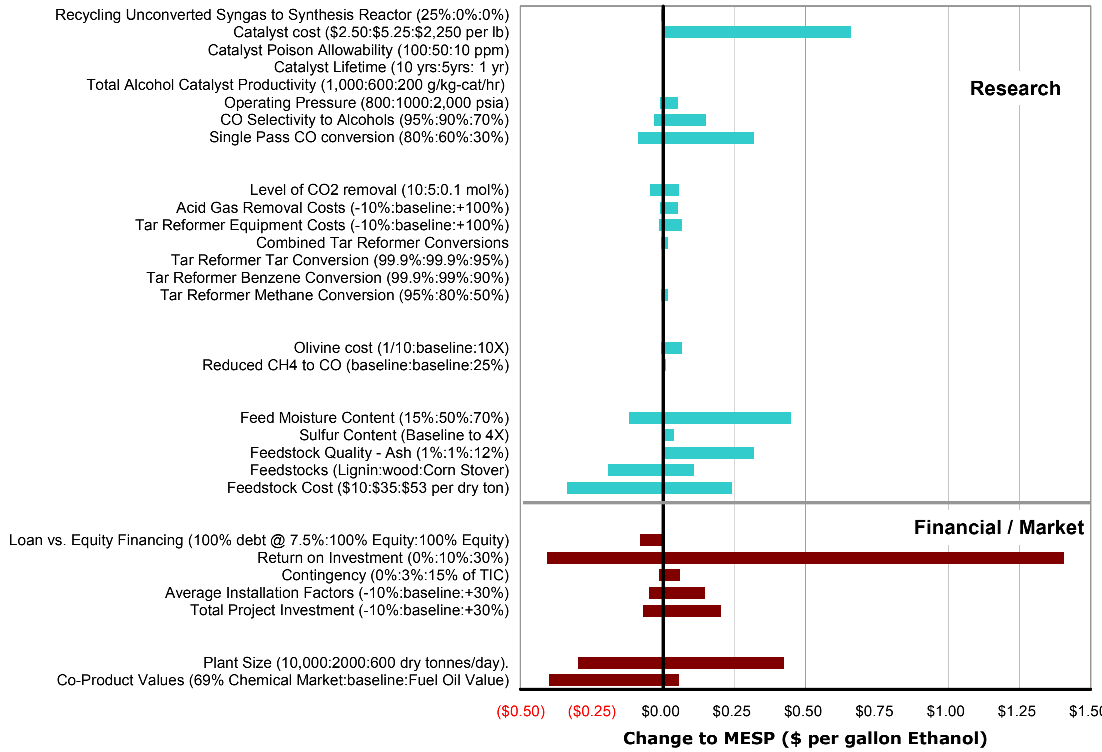


Figure 4-14. Thermochemical Process Sensitivity Analysis

4.2.3 Long-Term Technology Targets for the 30x30 Market Goal

Achieving the intermediate technology target of $1.07/gallon ethanol in 2012 will enable a viable lignocellulosic ethanol industry. Ethanol from lignocellulosic feedstocks will then join ethanol from starch feedstocks to displace imported petroleum and provide a sustainable, renewable resource for the nation's transportation needs. However, market analysis (see Section 2) indicates that displacing 30% of 2004 gasoline demand with ethanol by 2030 will require additional technology advancements and the continued reduction of feedstock supply system and processing costs. This is predominately driven by the need to capture higher cost feedstocks to meet the 30x30 goal.

Future R&D efforts will focus on four complementary approaches. Independently, the approaches will not result in technology improvements that will meet the 30x30 goal. However, collectively, they combine revolutionary scientific breakthroughs with evolutionary process developments to meet the 30x30 goal.

Some cost reductions will be achieved by continuous process improvement to technology developed to meet the 2012 target. For example, the construction and operation of full-scale biorefineries will highlight opportunities for unit operation optimization and provide operational experience for process optimization and cost reductions. The accumulation of operating experience and engineering data will enable the design of larger-scale biorefineries, which will further reduce biofuels production costs by leveraging economies of scale.

These are the evolutionary cost reductions. More dramatic cost reductions will be required from scientific breakthroughs to reach the reduced conversion cost target of 2030. (See Section 2 for an explanation of the effect of this cost reduction on market penetration.)

Earlier sections of this report described technologies for feedstock supply systems, biochemical conversion, and thermochemical conversion to accomplish the 2012 technology target. In the future, advancements will be made in all three areas, and there will be opportunities for cost savings through the integration of the two conversion technologies and through larger facilities. See Section 1 for a delineation of the cost targets for the advanced state of technology research goals.

The four areas of future technology advancement to accomplish the 2030 goal are:

1. Advanced, large-tonnage feedstock supply systems
2. Systems biology to improve biochemical processing
3. Selective thermal transformation to improve thermochemical processing
4. Technology integration, economies of scale, and evolutionary process optimization.

4.2.3.1 Advanced, Large-Tonnage Feedstock Supply Systems

By 2012, functional feedstock supply systems will be demonstrated for all major biomass resources. Feedstock R&D will then shift to increasing the accessible biomass tonnage to enable production of 60 billion gallons of ethanol/year. As the biorefining industry expands, process improvements will drive biorefinery capacities up. Therefore, the longer-term feedstock supply R&D challenge is to ensure supply systems do not limit biorefinery size or consume biorefinery profits that could be used to purchase higher-value feedstocks (see Figure 4-15). By increasing the purchase price for feedstock up to about \$50/ton, all of the feedstock required to produce 60 billion gallons of ethanol can be accessed (see Appendix D). Adding estimated feedstock supply system costs gives a final feedstock cost of about \$70/ton. Notice that linear cost increases do not produce linear tonnage estimates. The \$70/ton cost is a maximum feedstock cost for only the largest tonnage levels.

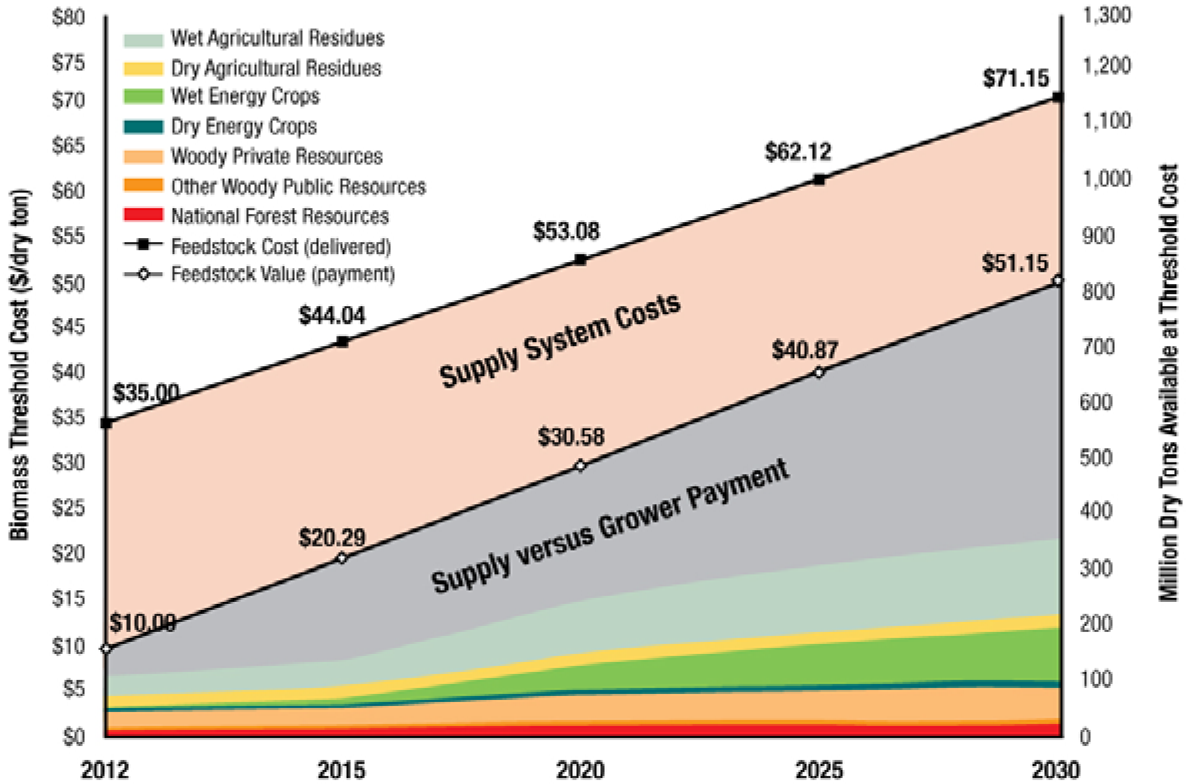


Figure 4-15. Advanced Feedstock Supply System Technologies: Value-Add Feedstock Pre-Processing

An advanced feedstock supply system will be needed to collect the large tonnages of feedstock required for large-scale biorefineries. An efficient interface between producers and the commodity biomass system is important for large-scale feedstock supply technology development. Production, harvesting, and collection systems will be widely varied, based on biomass resources and local practices. Primary research needs include storage, pre-processing, and transportation systems suited to these varied systems.

The development of value-add feedstock pre-processing and blending technologies will provide flexibility in the biomass feedstock supply system and allow suppliers to:

1. Reformat/condition different feedstocks into a common format and quality
2. Fractionate secondary co-products for local markets
3. Produce blended, large-scale commodity biomass.

Value-add pre-processing will help create a market specification for feedstocks (which will help in the transition of biomass to a large-scale commodity) and ensure that feedstocks from varied sources can supply a large-scale biorefinery without process upset.

Advanced Feedstock Transportation and Handling Systems

Advanced feedstock supply systems will also rely heavily on new transportation methods and technologies to take advantage of the value-add pre-processing and merchandising of raw feedstock material. Truck transportation may not be economically possible because of transport distances, traffic congestion, and community opposition. Rail transport reduces load frequency, but it is often more expensive than truck transport because of infrastructure constraints. Advanced transportation systems will likely incorporate technologies that not only provide infrastructure and operational cost savings but also in-transit value-add processes.

4.2.3.2 Systems Biology to Improve Biochemical Processing

Systems biology research will result in improvements to feedstock to maximize the recoverable liquid fuel per acre of land and drastically simplify the conversion process. These improvements have the potential to reduce the cost of converting lignocellulosic biomass to ethanol by about 30% for a similar sized 2,000 ton/day facility as the 2012 $1.07 target. Additionally as the advanced state of technologies facilitate larger scale facilities, an additional cost of production benefit of about 40% could be realized for a 10,000 ton/day operation. These kinds of cost reductions are typical of conversion technologies as they mature. The oil industry, corn industry, and others have seen processing costs drop dramatically over time until feedstock is the predominate cost.

It is envisioned that, through systems biology, the overall conversion process can be simplified and capital and operating costs can be reduced (see Figure 4-16).

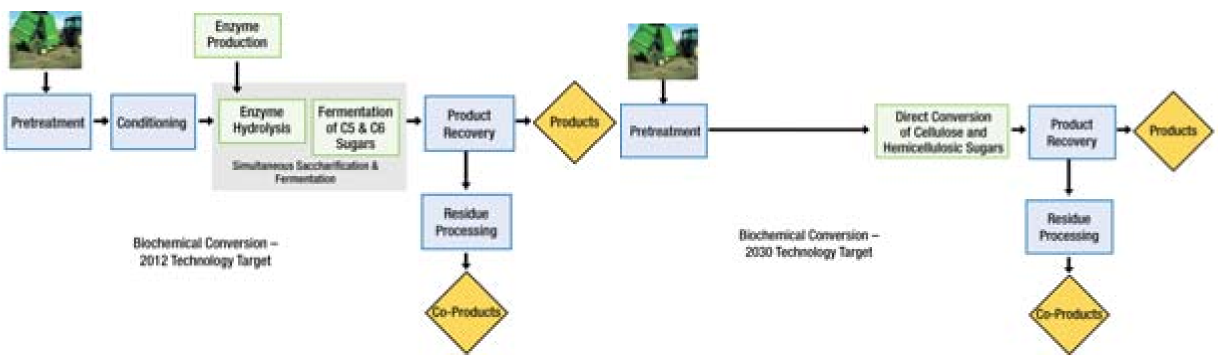


Figure 4-16. Process Simplification through Systems Biology Research

The advanced technology will combine several unit operations and improve the pretreatment operation. Enzyme production and fermentation will be combined in a single organism. Thus, with enzyme produced during saccharification and fermentation processes, the three process operations are combined into one. In addition, more robust micro-organisms will eliminate the need for hydrolyzate conditioning. These technology improvements will lower the total capital cost (project cost) of a 2,000dry ton/day facility by about 22% (Jechura 2006a) from $2.66/installed annual gallon of ethanol capacity (for the 2012 technical target). Combining the technology improvement and the larger scale of a 10,000ton/day facility lowers the total capital cost to $1.44/installed annual gallon (Jechura 2006a).

Translational science concepts will be adapted to pursue these advancements. This approach, familiar to the biomedical industry, integrates basic research (or fundamental biological science) with industrial application (such as bio-engineering). To meet the 2030 technical target, significant fundamental science must be completed. To accomplish this in the available time frame, the research activities of DOE's EERE and Office of Science must be coordinated.

The Office of Science has developed an extensive roadmap for its systems biology research approach to this endeavor (Thomassen and Johnson 2006).

The following section and Table 4-5 describe the research required to accomplish the 2030 technical target for biochemical conversion.

Fundamental Biological Science
A full and detailed integration of science and engineering research will lead to the most efficient process development plan. Fundamental R&D in biomass conversion must be targeted to process improvements based on technical barriers. An integrated fundamental and applied research program in biochemical conversion must include advancements in three areas:

Feedstock engineering

Develop GTL and agronomic/silvicutlure strategies to maximize the yield and quality of developing energy crops.
Design and manipulate plant cell wall composition and structure to maximize the yield of fermentable sugars.

Cell wall saccharification

Analyze glycosyl hydrolase structure/function as it applies to plant cell wall deconstruction.
Develop improved (engineered) enzymes for advanced biochemical conversion technologies, and integrate them with pretreatment chemistries.

Strain development

Apply systems biology and biochemistry to strain improvement to increase the conversion of sugars released during biomass deconstruction to ethanol and products.
Focus on strains that will produce saccharifying enzymes and ferment the resulting sugars to ethanol.

The detailed R&D strategies of these research areas are presented in Appendix G.

Table 4-5. Timeline of Key Activities to Accomplish the 2030 Biochemical Technical Target

R&D Area	Completion Year: Current	2015	2020	2030
Feedstock Engineering	E1 cellulase expressed at 2% in Arabidopsis Aspen demonstrated with 15% increase in cellulose		Demonstrate cellulase expression in feedstocks at economically viable level	Demonstrate energy crop cultivation with 25% increase in carbohydrates
Cell Wall Saccharification	Cell walls have been studied from a synthesis perspective but not a deconstruction perspective Enzyme hydrolysis at \$0.32/gallon ethanol produced	Develop and apply systems biology methods (e.g., high-throughput and computational simulation) for enhanced understanding of the basic science questions in biomass conversion	Demonstrate >5x improved cellulase activities based on a more complete understanding of cell wall deconstruction	Demonstrate feedstocks with modified cell walls and new enzymes that easily digest and have high yields of fermentable sugars
Strain Development	Limited hydrolyzate sugar conversion		Develop organism for single-step processing that compares with commercial fermentative organisms and enzymes in laboratory fermenters	Develop commercially available organism for single-step processing that produces ethanol yields and productivities comparable with existing individual organisms
Engineering Research		Identify the best pretreatment technology for use with single-step biological processing in the laboratory	Operate a pilot-scale pretreatment for single-step biological processing with multiple feedstocks	Combine best pretreatment and organism for single-step biological processing into an integrated pilot plant

Bio-Engineering Research
The objective of bio-engineering research is to acquire new understanding in broad-based aspects of applied process engineering research. An example is the support of experimental consortia (e.g., the multi-university Biomass Refining Consortium for Applied Fundamentals and Innovation) that propose to develop improved biomass pretreatment processes and feedstock qualification work to build databases for those considering new feedstock options for process design. The application of commercial enzyme preparation components to various pretreated biomass samples, within and beyond the scope of established consortia, is also a function of 30x30-impacting engineering research. This work will extend the comparative pretreatment analysis to multiple feedstocks (e.g., corn stover, switchgrass, and hybrid poplars) and additional pretreatment process impacts (e.g., the identification of hydrolyzate conditioning requirements for different pretreatments).

The applied research program required to meet 30x30 objectives will include advancements in process application knowledge at two levels. The first will address process-related engineering research that converts new understanding from fundamental research to the biorefinery context. The second will use process-related engineering information to develop recommendations for industry regarding process parameters, equipment, and operating conditions.

Process Unit Operation Engineering
This work targets the interface between fundamental science and process-scale integration engineering. Again, the objective is to acquire new understanding in broad-based aspects of applied process engineering research, potentially through experimental consortia, such as the Consortium for Applied Fundamentals and Innovation.

4.2.3.3 Selective Thermal Transformation to Improve Thermochemical Processing
Achieving the 2012 technology target for biomass gasification – mixed-alcohol synthesis – requires improvements in catalytic tar and light hydrocarbon reforming to increase conversion efficiencies and reduce the capital costs of syngas cleanup and conditioning. To further improve thermochemical conversion to meet the 2030 technical target, two complementary approaches will be adopted:

- Pursue scientific achievements to improve yields and efficiencies and maximize process integration opportunities in existing thermochemical processes (engineering approach)
- Use a rigorous research program to investigate fundamental biomass thermochemical conversion to enable alternative processes that will help erase the lines between gasification and pyrolysis as separate technology options (scientific approach).

R&D efforts for thermochemical technology will focus on the front end of processes while the downstream unit operations continue to be optimized. Significant improvements in catalytic gasification will be made to increase carbon conversion efficiencies to syngas and decrease tar formation. Within the gasifier, this converts 50% of the methane produced during biomass gasification to carbon monoxide and hydrogen (the syngas components required for downstream conversion to ethanol). Throughput of the gasifier also increases 25%. This improved technology will reduce thermochemical conversion cost by 38% over the 2012 technology target (Spath 2006).

Process consolidation will continue to lower capital and operating costs to meet the technology cost targets. The block flow diagram in Figure 4-17 illustrates the R&D required to advance thermochemical conversion technology and meet the 2030 technology target.

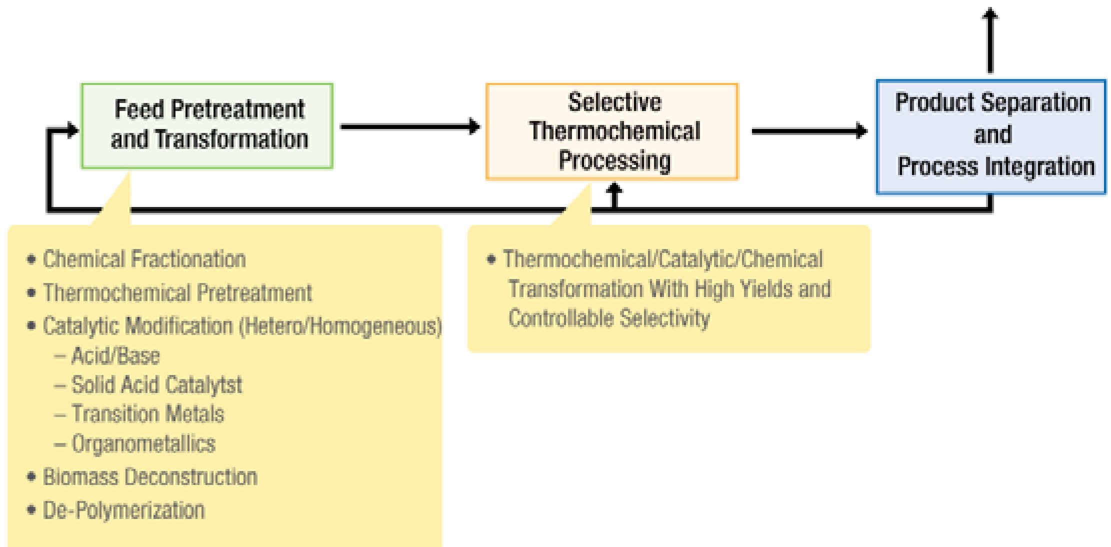


Figure 4-17. Selective Thermochemical Processing

The following sections and Table 4-6 describe the research needed to accomplish the 2030 technical target for thermochemical conversion.

Catalytic Gasification and Pyrolysis
Since the beginning of coal gasification, catalysts have been sought to improve carbon conversion to products and increase gasification rates while minimizing temperature to increase process efficiency. Alkali metals have long demonstrated catalytic activity in steam gasification of solid fuels, and metal-based catalysts—particularly nickel-based materials—are active and effective for hydrocarbon reforming.

Lignin Utilization
The integration and use of lignin residues will be key to establishing the commercial viability of lignocellulosic biorefineries and maximizing biomass use for fuel production. Because lignin is a complex but lower-value biomass component, it is essential that new technologies increase its value to enhance the competitiveness of integrated biorefineries.

Biomass Deconstruction/Pretreatment
Technology advancements in these thermochemical processes highlight the need for breakthrough R&D to optimize the fractionation of biomass and provide separate feed streams with compositions suitable for specific conversion technologies.

Selective Thermal Transformation of Fractionated Biomass
A range of alternative conversion options is envisaged through the fractionation of biomass into specific components. A narrower, more uniform biomass fraction opens the possibility of developing thermochemical conversion options with high yields and selectivities.

Table 4-6. Timeline of Key Activities to Accomplish the 2030 Thermochemical Technical Target

	Completion Year			
R&D Area	**Current**	**2015**	**2020**	**2030**
Catalytic Gasification	New	Identify viable catalysts for use in the gasifier to modify the product gas in the laboratory	Increase carbon efficiencies to syngas Reduce methane produced to 50%	Use biochemical process residue from a combined process with previous carbon yields at integrated pilot-plant scale
Lignin Utilization	Heat and power generation	Identify the best process for thermochemical use of lignin	Verify the best process for thermochemical use of lignin at the laboratory scale	Verify the best process for thermochemical use of lignin at an integrated pilot-plant scale
Biomass Deconstruction/ Pretreatment				Validate integrated biochemical-thermochemical process that pre-fractionates biomass to optimize conversion efficiency of carbohydrate-rich streams and lignin-rich streams

4.2.3.4 Technology Integration, Economies of Scale, and Evolutionary Process Optimization

Biochemical and thermochemical conversion technologies can be integrated for additional efficiency and cost improvements. Biochemical conversion extracts the carbohydrate portion of the feedstock and then converts it to fermentable sugars and, ultimately, ethanol. The remaining residue, primarily lignin, cannot be fermented, but it is a valuable organic feedstock. By directing this byproduct to a thermochemical process, it can be converted to syngas and, ultimately, ethanol. The integration of these technologies will improve the energy efficiency of the process, lower costs, and produce more ethanol than a standalone biochemical or thermochemical process.

Recent studies have examined other thermochemical conversion options coupled with biochemical processes. One study evaluated the economics of integrating advanced biochemical conversion (consolidated bio-processing) and gasification with single-pass Fischer-Tropsch synthesis (Lynd et al. 2005). The processes had substantial heat integration and byproduct electricity production. The analysis showed additional fuel could be produced, but the incremental capital cost (on a per-gallon basis) increased. An integrated biorefinery can increase liquid fuel yield beyond the maximum from carbohydrate-only conversion, but there is an incremental increase in capital cost to do so.

Figure 4-18 depicts the advanced, integrated biochemical and thermochemical alcohol production scheme analyzed. Some of the lignin-rich residue is used to provide steam and electricity to the biochemical process, and the remainder is processed in the thermochemical process. The larger biochemical processes (8,000 -10, 000 metric tons/day) expected in the 2020–2030 time frame will be needed to feed a reasonably sized gasification plant (1,500 - 2,000 metric tons/day) with only lignin-rich residues. The scale of the biochemical processing plant is five times larger than that targeted for 2012, but the scale of the thermochemical conversion plant is the same.

This combined process can maximize feedstock handling efficiencies and heat and power integration. Integrated biorefineries can also process feedstocks with both high and low carbohydrate contents. A steady supply of low-carbohydrate feedstock could be fed directly into the thermochemical process, which allows increased size and some benefit to the capital cost. Integrated biochemical-thermochemical biorefineries also capitalize on the process improvements identified in the independent developments of the two technologies.

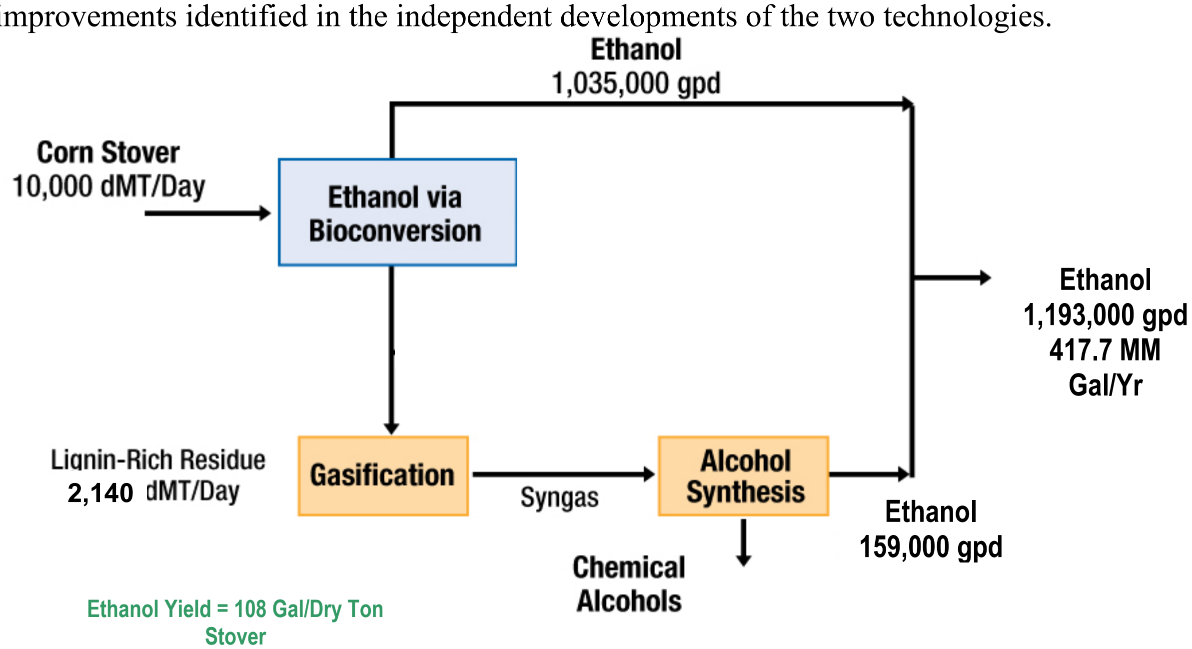


Figure 4-18. Integrated Biorefinery Gasification Scenario with Excess Lignin Converted to Ethanol

5. Ethanol Storage, Distribution, Blending, and Vehicle Infrastructure Needs

5.1 Existing Ethanol Distribution Infrastructure

The existing corn grain ethanol industry transports approximately 5 billion gallons of ethanol each year. The process for delivering ethanol from the production plant to the consumer is illustrated in Figure 5-1.

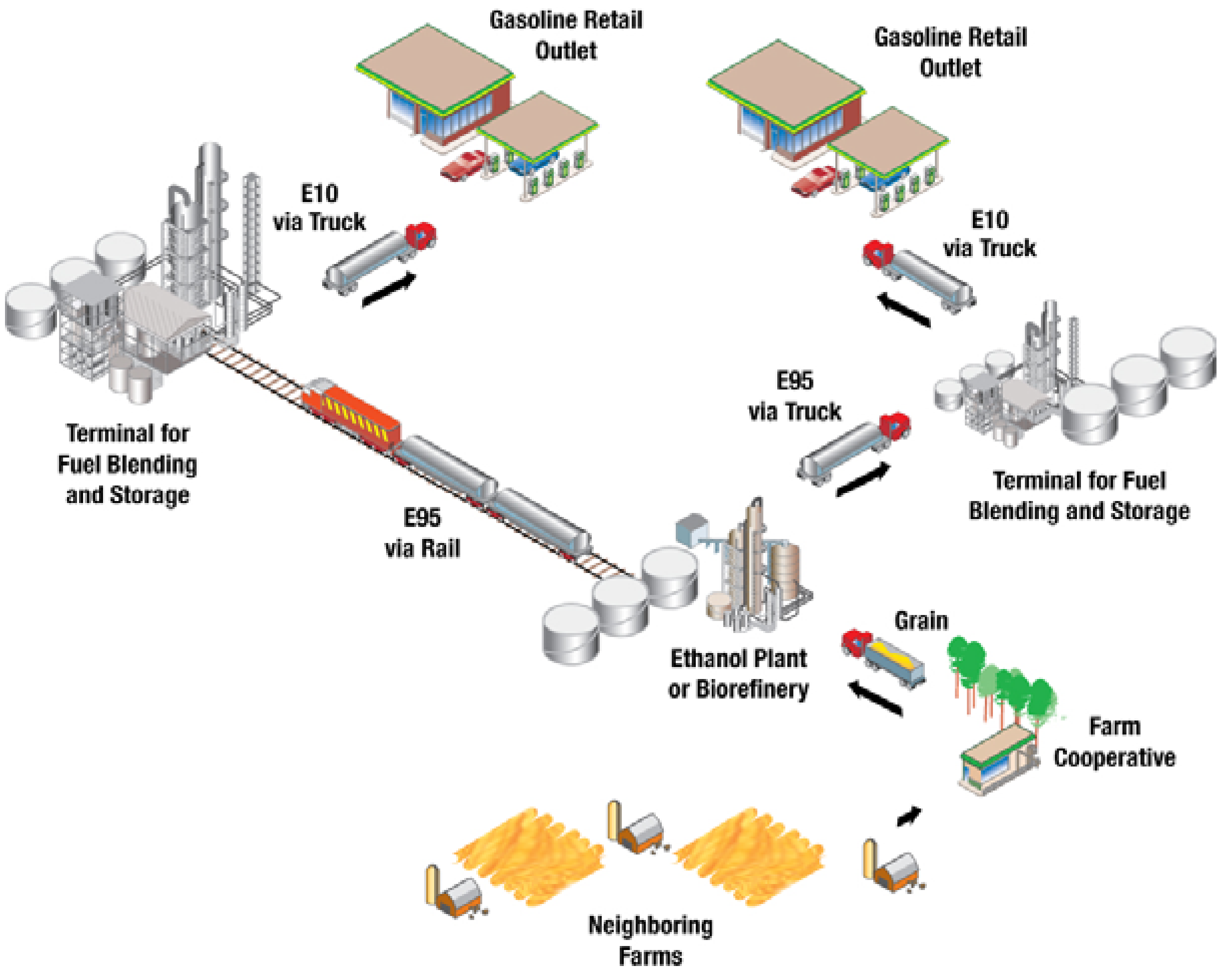


Figure 5-1. Existing Ethanol Distribution System

Ethanol is denatured with gasoline to form a blend of 95% ethanol and 5% gasoline (called E95 or fuel grade ethanol) and stored at the plant. The purity and properties of fuel grade ethanol are specified in ASTM D4806. Shipping is by rail or tanker truck to wholesale gasoline terminals, where the E95 is stored in specialized tanks until it is blended into gasoline. To blend, the terminal operator adds ethanol into a load of gasoline in a tanker truck or rail tanker car (called “splash” or “top-off blending”) and relies on the movement of the truck or tanker during transit to mix the blend. Alternatively, the operator can use an inline system to blend the ethanol into the gasoline in the terminal piping and then feed the blend into the tanker truck or rail tanker car.

E10 pumps are available at service stations throughout the Midwest, East, and West Coast and in many urban areas designated as non-attainment areas for air quality by the U.S. EPA. There is no census of how many of the 169,000 gasoline retail outlets in the United States carry E10, but market penetration is remarkably high in some parts of the Midwest (National Petroleum News 2005). In Iowa, for example, 65% of all gasoline sold in 2004 was blended with ethanol (Iowa, 2006).

Approximately 600 service stations nationwide dispense E85 blends, which consist of 85% ethanol and 15% gasoline (Downstream, 1999). [In reality, E85 composition varies seasonally, particularly in colder climates. For example, in winter, E85 is in fact a minimum of E70 in Minnesota and a minimum of E79 in Texas (National Ethanol 2006).] The properties of E85 are specified in ASTM D5798. Four hundred thirty of these stations are located in the Upper Midwest states of Minnesota, Iowa, South Dakota, North Dakota, Wisconsin, and Illinois (American Lung, 2006). Some are public, and others service state or federal FFV fleets.

E85 delivery and storage systems are virtually identical to those for E10. E85 can be splash-blended at the terminal and delivered by dedicated tanker truck to dedicated underground tanks at service or fleet refueling stations. It can also be blended at the retail station in the E85 underground tank.

Although this distribution infrastructure is sufficient for existing ethanol production, significant enhancements will be required to meet the 30x30 goal.

5.2 Infrastructure Changes Required To Meet the 30x30 Goal

As explained previously, the ethanol infrastructure from the plant to the consumer has four distinct parts:

- Storage
- Distribution (transportation from the plant gate to refueling stations)
- Blending
- Refueling.

To ascertain how the infrastructure will develop and determine associated costs, each part of the infrastructure was considered individually. Each section was investigated on the basis of cost per gallon of ethanol delivered, total capital cost, and logistical issues and technical challenges. Distinctions were not made among the types of fuel delivered (i.e., among E10, E20, E85, etc.).

5.2.1 Storage

Two major assumptions, based on the storage practices for petroleum products, were used for the storage of ethanol (Reynolds 2006):

1. The storage volume required is 10% of the cumulative production rate plus 30% (of the 10%) for inventory receipts and extra working space.
2. The installed cost for storage in conventional tanks is $22.40/barrel.

Based on these assumptions, total capital investment for storage will be approximately $4.15 billion. The fully loaded cost per gallon of ethanol is approximately $0.07/gallon.

Developing the storage infrastructure is relatively straightforward because a robust fuel storage industry is already well developed in the United States. Hence, developing the necessary storage infrastructure should not be a hurdle to the 30x30 goal.

5.2.2 Distribution (Plant to Pump)

This is the most complicated infrastructure needed to meet the 30x30 goal, and it will likely require the largest effort. Essentially, three approaches could meet 30x30 needs:

1. Continue development of the existing ethanol distribution infrastructure
2. Leverage the existing gasoline distribution infrastructure to distribute ethanol
3. Develop a new infrastructure that is optimized for the distribution of ethanol at the 30x30 scale and beyond.

5.2.2.1 Continue Development of the Existing Ethanol Distribution Infrastructure

This likely will be the preferred option in the near term because it is the least risky technically and it can accommodate the near-term growth in ethanol production projected in Section 2. However, there are serious issues related to the suitability of this infrastructure for the ethanol production volumes envisioned in the 30x30 goal.

This section analyzes three possible modes of ethanol transport from the plant gate to the distribution terminals: truck, rail, and barge. See Appendix I for a detailed description of the ethanol shipments required to meet the 30x30 goal.

Trucks are used primarily for short-haul routes. Although trucks are less efficient than barges and railcars, they provide rapid transport to nearby gasoline blending terminals. Tanker trucks are also used in most markets to transport E10 to local retail outlets.

Rail transport has a significant cost advantage over trucks when greater distances or volumes are involved. As ethanol-related demand for rail transport has grown, the system has evolved from single cars to dedicated trains (often referred to as “unit trains”). An increase in ethanol production to meet the 30x30 goal would require additional rail cars and lines.

Barges can move large quantities of fuel cheaply along major navigable waterways. Each barge can handle 10,000–30,000 barrels of fuel. Ten thousand-barrel barges routinely move ethanol up and down the Mississippi and Missouri river systems and to Gulf Coast blending points.

River and coastal barges will continue to serve as a low-cost option to transport ethanol to Gulf Coast states, the East Coast, and pipeline terminals (when and if they begin to accept ethanol).

Table 5-1 shows the distribution for ethanol shipping using these transportation modes (Reynolds, 2006). Reynolds estimated the distribution breakdown among barge, rail, and truck for 42 billion gallons of ethanol annually. The units, gallons shipped, and dollars invested were extrapolated to 60 billion gallons for the 30x30 scenario. In this scenario, trucks are used only for short distances: plant to distribution terminal and distribution terminal to service stations. For longer shipping distances, unit trains and barges are used because they are lower-cost options. The capital investment for each mode of transportation was depreciated using a 15-year MACRS (Modified Accelerated Cost Recovery System) method.

Table 5-1. Infrastructure Requirements to Reach 60 Billion Gallons by 2030

Mode	% of Ethanol Shipped	Units	Gallons (Billions)	($ Billion Gallons 2004)
Barges	20%	317	12	0.51
Railcars	22%	10,536	13.2	0.68
Trucks	54%	6,490	32.5	0.81

Feasibility studies and business plans commonly use the ranges shown in Table 5-2 to estimate costs from the plant gate to the blending terminal. Assuming the same trucking rate and a radius for ethanol transport from the blending terminal to pumps, we can estimate the delivered ethanol cost from plant gate to pump.

Table 5-2. Estimated Plant Gate to Pump Costs[a]

Plant Gate to Final Blending Terminal	Range (Miles)	Type	Cost ($/Gallon)
Local[b]	0–150	Truck	$0.03–$0.04
Regional[c]	150–450	Truck or rail	$0.07
National[d]	450+	Truck to rail or barge	$0.11–$0.15
Blending Terminal to Pump	75–100	Truck	$0.02–$0.03
Total Cost From Gate to Pump Cost/Gallon	Local $0.05–$0.08	Regional $0.09–$0.10	National $0.13–$0.18

[a] From a June 15, 2006, conversation with Mark Yancy from BBI International.
[b] Fully loaded truck rate assumed $70/hr.
[c] 450 miles is an average 8-hour trucking day. No appreciable benefits are seen for rail in this range.
[d] Transport from Nebraska to the West coast is $0.12–0.15/gallon. It is slightly less expensive to the East Coast.

Conventional distribution methods have a variety of logistical issues. One issue is the strain increased ethanol distribution would add to already overloaded infrastructures (e.g., roads, rail lines, and waterways). Equipment capacity has been tight for several years, and the recent demand surge has exacerbated the difficulties (D'Amico, 2006). A substantial increase in costs for all types of carriers has been driven by increased demand and the cost of steel.

Other issues are specific to the transportation mode.

- Trucking issues include road traffic, filling and emptying delays, and fuel use.
- Rail issues include the increased burden on existing rail lines and the cost and logistical issues associated with building new lines to accommodate demand
- At issue with barge transportation is inter-coastal waterways traffic. Locks along the major rivers (i.e., the Mississippi, Missouri, and Ohio) are advanced in age and undersized for even current transportation load. This already causes long delays during peak transportation months. Another issue, especially in major Midwestern peak ethanol production areas, is that the upper Mississippi and Missouri rivers are closed for up to three months each winter because of ice blockage.

Given these costs and logistical challenges, meeting the distribution needs of the 30x30 goal with this option is quite challenging.

5.2.2.2 Leverage the Existing Gasoline Distribution Infrastructure to Distribute Ethanol
Pipelines are a mature transportation technology, and they are considered the safest way to transport fuels in bulk. Pipelines are typically the least-inexpensive mode of shipping large quantities of liquid and gaseous fuels (e.g., crude oil, gasoline, diesel fuel, and natural gas). There are an estimated 72,000 miles of product pipeline in the United States. With predictions that the world is approaching peak oil production, it is possible there will be excess pipeline capacity in the future that could be used to transport ethanol or gasoline-ethanol blends.

The ethanol industry could use the gasoline/product pipeline currently used by the petroleum industry if:

- There is unused pipeline capacity, which would allow ethanol to be shipped (in agreement with current pipeline owners)
- The technical barriers that keep ethanol from being mixed in pipelines can be overcome.

One advantage of leveraging the existing petroleum pipeline infrastructure is the maturity of the petroleum industry. Blending, distribution, and logistical issues have already been solved. In addition, minimum capital would be needed to ship large quantities of fuel.

Potential barriers include the ebb and flow of petroleum supply in the pipeline, which limits the ethanol that could be shipped on a spot basis. This could have a volatile impact on spot ethanol prices in the marketplace. However the main barrier is technical in nature. Currently, pipelines are not used with ethanol or gasoline blends that contain ethanol because of solvent and water issues (Reynolds, 2006).

Pipeline transport is problematic because:

- Ethanol is a stronger solvent than the petroleum products moved via pipeline. Consequently, ethanol will remove water, rust, gums, and other contaminants in the system. This can result in contamination and discoloration of the ethanol or gasoline-ethanol blend. This, in turn, downgrades the value of the product and adds backend costs to bring the product back to specification.
- Alcohol has a strong affinity for water. Ethanol would pick up water present in the pipeline system. Ethanol gasoline blends with excessive content can phase separate at low temperatures, depending upon the amount of water entrained.
- Strategies have been proposed to solve these issues, and in some cases, small tests have been successful with gasoline-ethanol mixtures in dry pipelines. Gasoline-ethanol mixtures have also been shipped, successfully in pipelines, in other countries. Although it is unknown at this time whether U.S. pipeline operators would consider shipping ethanol blends, it is unlikely they would actually do so until ethanol production is large enough to justify the additional investments needed. At that time, they would likely also consider dedicated ethanol pipelines.

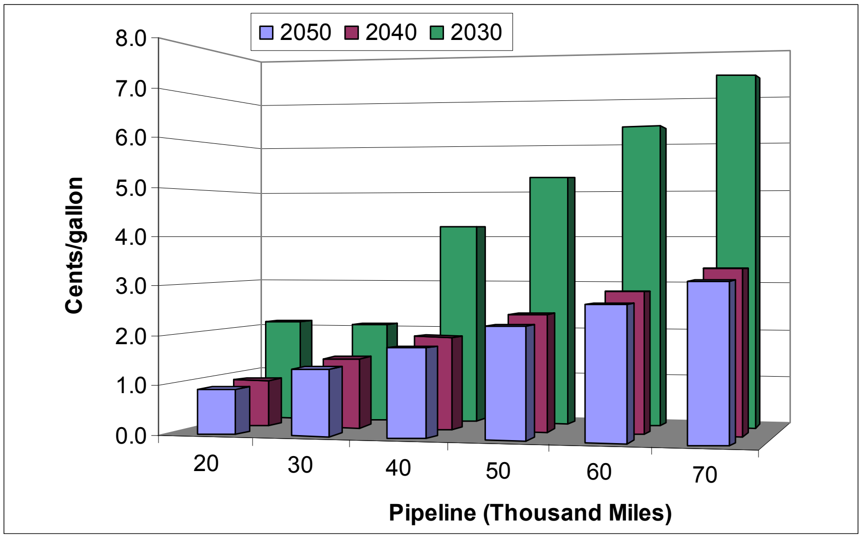
Defining a delivered cost per gallon for this scenario is difficult. In a best-case scenario, minimal capital investment would be incurred. The cost of fuel delivery from the plant to the pump would consist only of the cost of transport from the plant to the blending terminal and from the blending terminal to the refueling station. For cost estimation purposes we assume that the owners of the pipeline charge a fee, agreed to by all parties, as they do for hydrocarbon fuels, to use the delivery system. The cost to transport liquid fuels via pipeline is estimated to be $0.09/gallon based on current averages.

Clearly, this option is desirable. However, major logistical and technical issues, as stated above, must be addressed and overcome. In addition, this option is contingent on available capacity in the existing system to accommodate 60 billion gallons of ethanol.

5.2.2.3 Develop a New Infrastructure Optimized for the Distribution of Ethanol at the Scale of 30x30 and Beyond

The timing of dedicated ethanol pipelines will be a function of industry growth, the capacity of the distribution infrastructure, and the extent to which the ethanol industry can leverage the current pipeline system. However, dedicated ethanol pipelines will logically be built when the quantity of ethanol is large enough to justify the costs. Another factor that will influence large-scale pipeline transport is demand generated for fuel by vehicle fleet needs.

A rough cost estimate for pipeline is $1 million per mile installed (Reynolds, 2006). As with conventional transportation costs, pipeline capital is depreciated using MACRS depreciation for a 15-year period. Figure 5-2 shows average pipeline costs on a cost per gallon delivered basis for the entire 60 Billion gallons of ethanol for the 30x30 scenario from refinery gate to fuel distribution terminal.



These figures assume that all the ethanol from starch comes from PADD 2 (see above).

Figure 5-2. Ethanol Pipeline Costs

Even with a dedicated pipeline system, there will be a need for short-distance distribution from the plants to terminals and from terminals to refueling stations. Table 5-2 shows cost range estimates for ethanol delivered by dedicated pipelines. The later start dates are lower on a cost per gallon shipped basis because of the higher amount of ethanol that flows through the pipeline.

Comparing costs of the three options clearly shows that using the existing petroleum pipeline systems would be the lowest cost option, followed by dedicated pipelines, and finally expanding the current ethanol distribution system to meet the needs of the 30x30 scenario would be the highest cost option. This analysis does not include the logistical issues that would be associated with building new dedicated ethanol pipelines. The issue would need to be balanced and need to be balanced against alleviating the strain on the U.S. road, rail, and inner coastal waterway infrastructures.

Table 5-3. Distribution Costs Using Pipeline

Plant Gate to Final Blending Terminal	Range (Miles)	Type	Cost ($/Gallon)
Local	0–150	Truck	$0.03–$0.04
Regional or National	Any	Pipeline	$0.003–$0.09
Blending Terminal to Pump	75–100	Truck	$0.02–$0.03
Total Cost From Gate to Pump	Local		Regional or National
Cost/Gallon	$0.05–$0.08		$0.08–$0.16

In the end, there will likely be a combination of current infrastructure, leveraged petroleum industry resources, and dedicated pipelines. To investigate the options for ethanol distribution at this scale, experts from the U.S. Department of Commerce and U.S. Department of

Transportation as well as stakeholders in the ethanol and petroleum industries must be involved.

5.2.3 Blending

Currently, ethanol is denatured before leaving the plant gate, per Bureau of Alcohol, Firearms and Tobacco (BATF) rules. Denatured ethanol is transported to gasoline terminals, where it is splash-blended with gasoline. The blended product is then transported to end-user markets.

It is logical to assume that, as ethanol production increases and a geographical shift of ethanol distribution from the Midwest to the coastal United States takes shape, there will be changes in blending practices. As the light-vehicle fleet moves toward a dedicated E85 fleet, gasoline will be blended into ethanol. The estimated cost of installing terminal blending capabilities is approximately $200 million. However, blending costs are relatively insignificant when compared with storage and transportation costs. They add less than $0.005/gallon to final distribution costs. As is the case for storage, developing the necessary blending infrastructure should not be a major hurdle towards achieving the 30x30 goal.

5.2.4 Refueling Stations

Expanding ethanol consumption through the widespread use of E10 will have relatively few effects on the existing vehicle and refueling infrastructure. The gasoline refueling infrastructure is already compatible with E10, and many stations already dispense E10. The situation is similar for the existing vehicle fleet. Gasoline vehicles are already functionally compatible with ethanol blends up to E10. Therefore, preparing the refueling infrastructure and vehicle stock for E10 should require no capital investment.

However, increasing use of E85 involves hurdles. These include the availability of appropriate vehicles, the need for specialized refueling equipment, and the ability of drivers to choose their fuel based on convenience, price, and attitudes. Drivers must have FFVs, there must be conveniently located refueling stations, the fuel must be competitively priced on a miles traveled basis, and the vehicle's performance on E85 should at least match that of gasoline.

At an approximate cost of $25,000/refueling station retrofit, an installed capital cost of nearly $3 billion will be required over the next 30 years for storage and dispensing modifications for ½ the stations in the targeted PADDs (Appendix I). Using the same capital depreciation used previously, this equates to approximately $0.07/gallon.

5.3 Total Infrastructure Investments Required to Meet the 30x30 Goal

Table 5-4 shows the cumulative investments and the normalized cost per gallon of ethanol delivered from production plant to consumer.

Table 5-4. Total Infrastructure Costs

Infrastructure Section	Total Capital Cost (Billion $)[1]			Cost/Gallon Delivered ($/Gallon)		
Storage	$4.15			$0.07/gallon		
Distribution Option	1	2	3	1	2	3
	$2	$0	$20[2]	$0.15	$0.09	$0.12
Blending	$0.2			$0.003/gallon		
Refueling Infrastructure	$4.2			$0.07/gallon		
	1	2	3	1	2	3
Total	$10.5	$8.5	$28.5	$0.29/gallon	$0.23/gallon	$0.26/gallon

1 Storage, blending, and refueling costs were calculated by dividing the estimated capital by 60 billion gallons. All distribution costs were calculated using a 15-year MACRS depreciation period.
2 Based on the assumed 20,000 miles of pipeline required. See Appendix I for details.
3 Assumed fee charged by pipeline owner. This number is based on the average existing cost per gallon of gasoline shipped via pipeline.

As shown in Table 5-4, the biggest variable is distribution. If dedicated pipelines are required, they would represent the largest capital investment.

How and when the distribution infrastructure will be developed is the biggest unknown at this time. Achieving the 30x30 scenario will require that these critical issues be addressed.

5.4 Vehicle Fleet

Necessary vehicle fleet changes can be categorized into (1) vehicle requirements for E10, (2) vehicle requirements for E85, and (3) advanced vehicle technologies.

5.4.1 Vehicle Requirements for E10

As previously explained, the widespread use of E10 will have no effect on the existing vehicle fleet from an operability and durability perspective. There are, however, concerns about the potential for increased emissions caused by using ethanol. When ethanol is blended with gasoline, the fuel's Reid vapor pressure (RVP) increases, which leads to increased ozone-forming evaporative emissions from the vehicle and during refueling. This can be controlled by reducing the RVP of the gasoline stock into which the ethanol is blended. This is already done in many EPA ozone non-attainment areas. In non-attainment areas for carbon monoxide, the

EPA can grant a 1-psi maximum increase waiver for RVP requirements to allow the use of ethanol as an oxygenate to reduce carbon monoxide emissions. Additionally, ethanol can cause an increase in the permeability of fuel system hoses and seals that can increase evaporative emissions by up to 65%, independent of the efforts to limit or control RVP. There is also uncertainty regarding the impact of ethanol on tail-pipe emissions of NO_x and aldehydes. While some studies show little or no effect on these emissions other studies suggest that increases might be significant. Additional testing is warranted to alleviate the address air quality impacts of the 30x30 scenario. Appendix I details emissions concerns associated with E10.

5.4.2 Flexible Fueled Vehicles (FFVs) and Ethanol

Increasing the use of ethanol via E85 involves different hurdles. These include the availability of FFVs and the ability of drivers to select a preferred fuel based on convenience, price, and performance along with some slightly different environmental concerns. Ethanol capacity in the U.S. fleet includes conventional vehicles able to legally operate on blends of up to 10% by volume ethanol and FFVs that can operate on up to 85% ethanol.

FFVs are considered alternative fueled vehicles. Through incentives, the National Highway and Traffic Safety Administration gives vehicle manufacturers corporate average fuel economy credits for them. Therefore, FFVs have a tangible economic benefit to manufacturers and are offered to consumers at no incremental cost. Vehicle manufacturers estimate that the cost of converting a conventional vehicle to an FFV in the original manufacturing process is less than $100. Today, Ford, General Motors, and Daimler-Chrysler all manufacture, certify, and sell FFVs. These vehicles have proved to be as durable and clean as their conventionally fueled counterparts on the road and in the laboratory. However, because E85 is not as widespread as conventional gasoline at the pump, manufacturers have not thoroughly optimized vehicles for E85 operation.

A number of modifications are made to FFVs to enable E85 use. Material compatibility changes, such as using appropriately resistant and durable plastics and elastomers and corrosion-resistant metals, are necessary for acceptable performance. Fuel sensors, if used, must be able to interpret ethanol blend level. Other changes that are made so that the proper air-to-fuel ratio for complete combustion requires higher fuel flow and injection rates. Additionally, because of the roughly 20% higher octane rating of E85 than regular gasoline, the engine spark timing can be adjusted to improve efficiency such that FFVs running on E85 typically exhibit a 26% reduction in fuel economy, rather than the 29% expected based on fuel volumetric energy content (US EPA, 2005).

Overall, today's FFVs have been able to slightly take advantage of E85 properties using the methods described above to get a small improvement in engine efficiency. However, on a volumetric basis, consumers will notice a decrease in vehicle range when operating their FFVs on E85 instead of gasoline. This can be a deterrent for consumers when they are given a choice between E85 and conventional gasoline and will generally require that E85 cost less on normalized miles per gallon of fuel basis than gasoline, at least initially.

E85 has significantly lower vapor pressure than E10 or gasoline and in fact additional gasoline must be added to E85 in winter to achieve the minimum vapor pressure required for cold starting. Thus, evaporative emissions are not an issue, however in winter months E85 may actually need to be adjusted to have an ethanol content as low as 70%. We also have a poor understanding of the impact of intermediate (between E10 and E85) blends on evaporative and tailpipe emissions. These blends occur because consumers can commingle gasoline, E10 (or E5.7 Currently in California, and E85 in their vehicles. Although we expect E85 to reduce tail-pipe emissions relative to gasoline, little data exist on recent model year vehicles. Finally since few FFVs have significant operating history on E85, researchers need to validate the long-term durability of FFVs operating on E85.

In the future, manufacturers may convert the entire national fleet to FFVs. This would minimize vehicle manufacturing and certification complexities and increase national production and availability. Given additional supplies of competitively priced ethanol, the expansion of the FFV fleet would allow more drivers to refuel with E85. As ethanol production grows and the availability of FFV vehicles expands, it may even be possible to completely convert dispensers to E85.

In this analysis of the 30x30 scenario we use an aggressive scenario of FFV introduction, which is based on work done by the Union of Concerned Scientists for the Natural Resources Defense Council (Greene et al., 2005). Ethanol capacity in the U.S. fleet includes conventional vehicles able to legally operate on blends of up to 10% by volume ethanol and FFVs that can operate on up to 85% ethanol. The aggressive scenario assumes a linear rise in the percentage of light-duty trucks and cars sold annually that are flex-fuel capable, from around 2.5% today to just more than 50% by 2015. Under these conditions, growth in fleet capacity for using ethanol, as shown in Fig. 2-8, far outstrips the ability to deploy ethanol production facilities. Hence availability of FFVs should not be an impediment to achieving the 30x30 goal.

5.4.3 Advanced Vehicle Technologies

Advanced vehicle technologies are dedicated E85 vehicles with engines fully optimized for E85. These dedicated vehicles will have equivalent or enhanced performance on E85 but will not be able to operate on gasoline or E10. Engines specifically designed for ethanol would take advantage of ethanol characteristics such as high octane number, flame speed, and heat of vaporization to provide an efficiency increase that would largely compensate for the lower volumetric energy content of ethanol.

Engine designs to exploit the high octane rating of E85 have been developed. For example, Saab, using a 2.3-liter turbo-charged engine running on E85, showed a 20% improvement in engine performance (but did not calibrate for lowest tailpipe emissions) over baseline gasoline engines (Saab, http://www.saabo.com/index.php/category/enviromental 2006). The enhanced octane of E85 enables high levels of turbocharging and increased compression ratios boosting horsepower and efficiency. In principle, this should allow smaller engines to generate equivalent horsepower and, therefore, show fuel savings. In this country, however, some of the improvements would be sacrificed to control emissions to the extremely low levels required in the US. More advanced engine designs could also take advantage of the higher latent heat of vaporization of ethanol which causes charge cooling, leading to a higher charge density and increased power output and efficiency. Finally, the higher laminar flame speed of ethanol allows leaner air-fuel mixtures increasing the volume of working fluid, providing an additional efficiency improvement. Results of an engine designed and run on E30 showed a 10%–12% gain in fuel economy, which more than compensates for the 8% reduction in fuel energy density. As ethanol becomes a bigger component of the fuel pool for light vehicles, automakers will continue to improve engine technology to better use E85 as a fuel.

While ASTM quality standards currently exist for fuel grade ethanol (D4806) and for E85 (D5798), development of advanced engines and vehicles for operation on E85 will be enabled by development of improved ASTM standards.

6.0 Conclusions

This report presents a scenario for achieving the 30x30 goal of replacing 30% of the 2004 motor gasoline demand with biofuels by 2030. Achieving the 30x30 goal as presented in this report, is based on *Annual Energy Outlook* high oil price projections with the key objectives as follows:

- Continue to successfully deploy corn-based ethanol up to its maximum potential (9.3–17.2 billion gallons)
- Develop and demonstrate at the pilot scale biochemical and thermochemical cellulosic ethanol conversion technology at the $1.07/gallon market target by 2012
- Develop and demonstrate at the pilot scale advanced cellulosic ethanol conversion technology that reduces conversion cost from 64% of the total ethanol production cost to 22% in the $1.07/gallon case by 2030
- Provide two market incentives to accelerate the deployment of ethanol
- Continue the $0.51/gallon ethanol tax incentive until 2020
- Provide a $20/ton subsidy for cellulosic feedstocks until 2025
- Develop the necessary distribution and vehicle infrastructure.

As detailed in Section 2 only the scenario outlined above achieved the 30x30 goal, however for AEO reference oil price projections 80% of the 30x30 goal was achieved which would still significantly impact energy security and imported oil displacement. Section 3 analyzed the energy balance and environmental implications of the 30x30 scenario. It showed that achieving the 30x30 goal will be a significant step toward a more sustainable energy future for the United States.

In this analysis of the 30x30 scenario, we use an aggressive scenario of FFV introduction, which is based on work done by the Union of Concerned Scientists for the Natural Resources Defense Council (Greene et al., 2005). The aggressive scenario assumes a linear rise in the percentage of light-duty trucks and cars sold annually that are flex-fuel capable, from around 2.5% today to just more than 50% by 2015. Under these conditions, growth in fleet capacity for using ethanol far outstrips the ability to deploy ethanol production facilities. Hence availability of FFVs should not be an impediment to achieving the 30x30 goal.

A market-driven assessment was used to develop this scenario. Hence, like any scenario, it reflects some of the authors' personnel opinions about the best mix of technology targets and market incentives. Every attempt was made to substantiate targets chosen from the peer-reviewed literature or, in the case of the market incentives, indicated from existing incentives or incentives consistent with the goals of the Energy Policy Act of 2005.

The scenario presented here is not absolute, and it is not the only scenario for achieving high levels of biofuels use. However, it does provide a comprehensive, systematic analysis of what it will take to achieve the 30x30 goal. Ultimately, however, market factors will dictate how and when biofuels are deployed.

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Appendix A: Starch Ethanol Deployment

A.1 Near-Term Ethanol Production Expansion

The U.S. wet and dry mill ethanol industries are adding production capacity at unprecedented rates to meet demand for gasoline blends and the mandates of the Renewable Fuels Standard of the 2005 Energy Policy Act. The Renewable Fuels Association estimates there are 4.8 billion gallons of installed capacity in the United States, and 38 new ethanol plants or plant expansions—totaling approximately 2.2 billion gallons of new capacity—are under way (Renewable Fuels 2006). Therefore, installed capacity should reach 7 billion gallons in the near term, which is well on the way to meeting the terms of the Renewable Fuels Standard. It projects U.S. annual ethanol production will reach 7.5 billion gallons by 2012.

For a 30x30 biofuels scenario, it is necessary to project the contribution of starch-based ethanol and the timing of production. Four critical questions must be answered to make this assessment:

- How much will U.S. corn production expand in the next decade, and what portion of the crop will be available for ethanol production given other demands (e.g., exports, animal feed, and industrial uses)?
- How much ethanol can be produced from each bushel of corn available?
- What are the likely effects of the projected level of ethanol production on corn prices?
- What is the potential for ethanol production from other grain crops and sugars?

A.1.1 Corn Available for Ethanol Production in 2015

Corn production is a function of the yield of corn per acre and the number of acres planted. Numerous studies have looked at the near-term supply of corn grain in the United States based on projections for these parameters, but two studies serve as benchmarks for low and high projections of domestic corn production over the next decade.

- The USDA's *Baseline Agricultural Predictions*, released in January 2005, provides projections for key crops to 2014 and serves as the low projection. It projects U.S. average corn yield in 2014 to be 161.8 bushels/acre, harvestable acreage to be 76.6 million acres, and resulting production to be 12,395 million bushels (Interagency 2005).
- In contrast, the National Corn Growers Association (NCGA) provides the high projection. In its scenario, it projects yield to be 193 bushels/acre, harvestable acreage to be 78 million acres, and resulting corn production to be 15,054 million bushels.

The NCGA estimates that "whole corn" use in non-ethanol markets is 9.1 billion bushels in 2005/2006 (USDA/PRX). For this projection, this demand is assumed to remain constant until 2015. This assumption does not take into account the possible role that corn distillers dried grains with solubles might play in a ramped-up ethanol production scenario by reducing the corn needed for cattle feed.

Table A-1 shows the high and low cases of corn available for ethanol production in 2015 given these assumptions.

Table A-1. High and Low Corn Production Scenarios, 2014–2015

Scenario	Harvested Acreage (Millions)	Yield/Acre (Bushels)	Total Annual Corn Output (Million Bushels)	Corn Output Available for Ethanol Production (Millions)
High Case (NCGA)	78	193	15,094	5,954
Low Case (USDA Baseline Projection)	76.6	161.8	12,395	3,295

A.1.2 Ethanol Production for Each Bushel of Corn Available

Low and high projections are also appropriate in this case. The current dry mill industry average ethanol yield is 2.6 gallons/bushel. However, improved yield is expected in plants under construction because of economies of scale, higher fermentation titers, and improved fermentation organisms. In its high case, the NCGA projects yield will reach 2.89 gallons/bushel by 2015—close to the theoretical limit. However, because older, less-efficient plants will still be in operation in 2015, the low estimate is 2.81 gallons/bushel. Cross-walking the high and low projections of ethanol yield with total U.S. corn production projections gives the 2015 range of annual U.S. corn-based ethanol production of 9.2–17.2 billion gallons. See Table A-2.

Table A-2. High and Low Scenarios for 2014–2015 Corn-Based Ethanol Production

Scenario	Corn Output Available for Ethanol Production (Million Bushels)	Ethanol Yield (Gallons/Bushel)	Annual U.S. Ethanol Production (Billion Gallons)
High Case (NCGA)	5,954	2.89	17.2
Low Case (USDA Baseline Projection)	3,295	2.81	9.2

A.1.3 Likely Effects of Ethanol Production on Future Corn Prices

Under these scenarios, U.S. ethanol production capacity would increase from the current ~5 billion gallons/year to 9.2–17.2 billion gallons/year. Assuming this level of ethanol production from corn is achieved in 2015, corn ethanol production will account for 27%–39% of total U.S. corn crop consumption, compared with the current 2006 NCGA estimate of 15%.

The USDA and land grant universities have made various estimates of the effects this level of ethanol production would have on the price of corn. The projections vary according to yield per acre and number of acres planted because rising yield and increased acreage tend to blunt price effects as more supply enters the market. On the low-impact side, some researchers project only local price increases of \$0.10–\$0.12/bushel within a 15-mile radius of a new ethanol plant (Leer 2005), with minimal impact on national corn prices. On the high-impact side, some researchers project a nationwide effect of \$0.12/bushel by 2014 (Wilcox 2005).

The USDA baseline projections analysis combined this impact with other market drivers to project a \$0.55/bushel price increase in the 2004–2015 period, which would result in corn prices moving from \$1.90/bushel to \$2.45/bushel in that period (Interagency 2005). A complementary analysis by Ferris and Joshi of Michigan State University (2004) looked at the economic effects of implementing a renewable fuels standard and banning the use of methyl tertiary butyl ether as a gasoline additive. They found that corn prices, under various scenarios, could reach \$2.70 by 2007–2010 from their projected base of \$2.10/bushel in 2005. Notably, this projected increase is based on ethanol production of only 5 billion gallons by 2012. The authors note that even though farmers are expected to react to the higher prices by planting more corn and less other food and forage crops, this price response is still expected.

Using the range of a \$0.55–\$0.60/bushel increase in corn prices by 2015 and assuming a yield of 2.81–2.89 gallons/bushel, the production cost of corn grain-based ethanol (if all other costs remain stable) will increase by \$0.19–\$0.21/gallon. If the consensus 2004 dry mill production cost of \$0.91/gallon of ethanol is used, then this rise in the cost of feedstock alone will raise the U.S. starch ethanol production cost to \$1.10–\$1.12/gallon. This does not factor in recent sharp rises in the cost of natural gas and other key utilities. Included in the production cost of ethanol is the production cost and market value of distillers dried grains with solubles. A large increase in ethanol production could have a negative effect on the selling price of distillers dried grains with solubles because of flooding of the feed market. Therefore, the \$1.10–\$1.12 cost could rise even more.

A.1.4 Other Crops for Starch- or Sugar-Based Ethanol Production

Corn grain is the most abundant and economical source of starch in the United States. Corn is inexpensive, widely available, and easily processed. It traditionally is used as feedstock in wet and dry mill ethanol plants. If the U.S. dry mill and wet mill industries continue to expand rapidly, the increased use of corn is expected to have two effects on feedstock supply:

1. It will put upward pressure on the price of corn for ethanol production.
2. Other grains and sugars will become more attractive relative to corn for ethanol production if their prices remain stable.

One ethanol production option is to supplement or substitute common grains and sugars for corn as feedstock. The feedstock sources most often mentioned are wheat, sugar beets, sugar cane, sorghum, barley, and oats. Figure A-1 depicts annual U.S. production of these crops in relation to annual U.S. corn production. Combined production of these crops is equal to 43% of the U.S. 2004 corn crop based on USDA data.

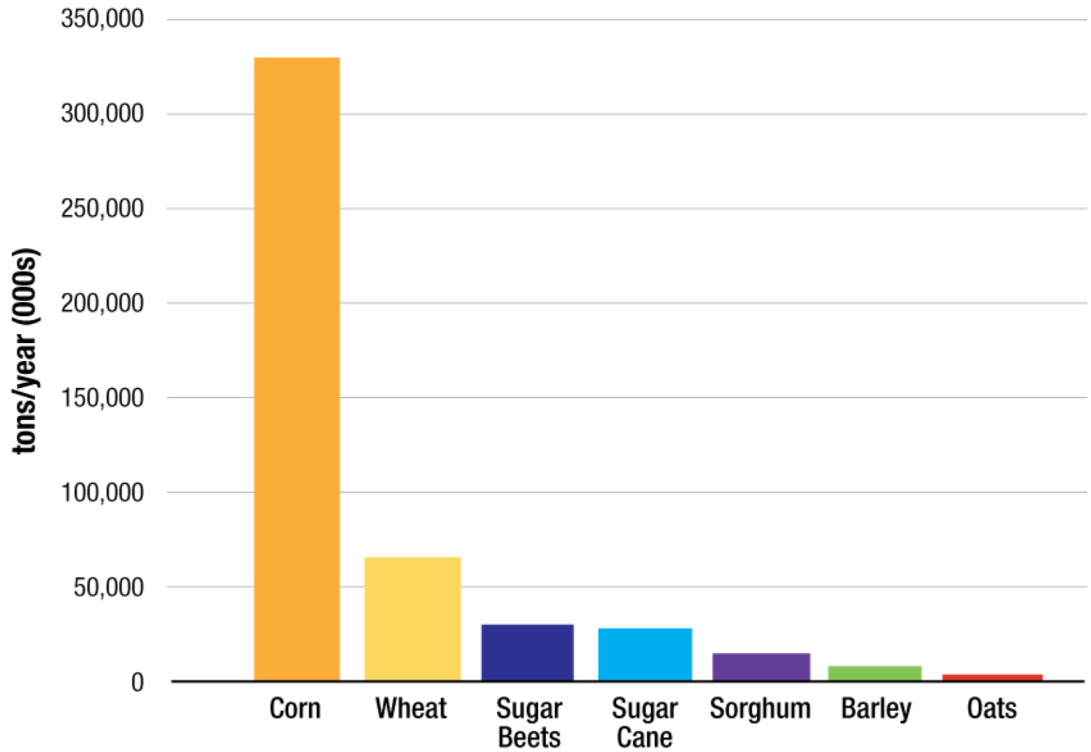


Figure A-1. 2004 U.S. Grain and Sugar Output

USDA crop estimates for 2015 (Interagency 2005) linearly projected to 2020 show that only corn and wheat production is forecast to increase markedly in this time frame. Current USDA projections indicate secondary grain and sugar crops will become less of a factor in U.S. agriculture over the next 15 years. Hence if current cropping trends continue, secondary grains and US grown sugar crops only offer modest opportunity for ethanol production based on volume.

Another key issue is how these crops compare with corn on a cost-normalized basis and whether market drivers can drive a dramatic increase in their production. Table A-3 (Statistics Service 2006, Kulp 2000) shows how cereal grain crops (i.e., wheat, oats, barley, and sorghum) compare with corn, and Table A-4 shows how U.S. sugar crops (i.e., sugar beets and sugar cane) compare with corn.

Barley, wheat, oats, and the sugar crops have current feedstock costs at least 40% more than corn. Because previously outlined enhanced ethanol production effects are not expected to raise corn prices by 40% in the next 10–15 years, it is unlikely—barring unforeseen reductions below historical norms of crop prices—that the other crops can compete economically with corn and hence they will not likely have a significant effect on ethanol production.

However, world sugar prices are considerably lower than U.S. prices. Hence, imported sugar could be economically viable for ethanol production. But because this analysis is for domestic ethanol production, this scenario is not evaluated. Therefore, market drivers do not exist to drive the increased production of these crops for ethanol production, and ethanol production from these crops is not considered in this scenario.

However, given the favorable economics of ethanol production from sorghum, which are actually lower on a cost-normalized basis than those of corn, enhanced ethanol production from sorghum merits investigation. To determine the potential for ethanol production from sorghum, a low bound is set at 27% of total annual average crop output and a high bound is set at 40%.The total acreage planted in sorghum is assumed to increase proportionately to meet non-ethanol demand. Table A-5 shows the ethanol production from this amount of sorghum use for ethanol production.

Table A-5. Ethanol Production from Sorghum

Scenario	Sorghum Output Available for Ethanol Production (Million Bushels)	Ethanol Yield (Gallons/Bushel)	Annual U.S. Ethanol Production (Million Gallons)
High Case (40% of Existing Sorghum Crop)	168	2.7	450
Low Case (27% of Existing Sorghum Crop)	113.4	2.7	310

Table A-3 shows that, even at these aggressive levels of sorghum utilization for ethanol production, this amount of production would have little effect on the 30x30 goal. Hence, ethanol production from sorghum is unlikely to play a major role on the national scale unless proper incentives are provided to transition large acreages into sorghum production.

A.2 The U.S. Potential for Grain/Starch Ethanol Production

Combining the potentials for sorghum with the potentials for corn gives total projections for U.S. grain/starch-based ethanol production in the range of 9.5–17.6 billion gallons. This ethanol production will be critical to the establishment of a large-scale market for ethanol as a low-concentration blend stock for octane enhancement (as E10) and as a commodity fuel (at the larger concentration of E85). Given the favorable economics and proven technology of grain ethanol compared with those of cellulosic ethanol, market factors will likely dictate that this level of grain ethanol production be deployed prior to market deployment of cellulosic ethanol. The exception will be if government incentives—such as cost-shared programs, loan guarantees and tax credits—are offered to make cellulosic ethanol more attractive.

In any case—even the high projection—grain-based ethanol is not sufficient to achieve the 60 billion gallons of ethanol production required to achieve the 30x30 goal. Cellulosic ethanol production in the range of 40–50 billion gallons by 2030 will be required.

Table A-3. Cereal Grain Comparison

Crop	U.S. Acres Harvested		Crop Yield		Bushel Weight	Moisture Content	% Starch	Crop Price			Ethanol Yield	Cost of Ethanol Production
	(Million Acres)	Trend	(Bu/Acre)	Avg	(Lbs)		(Dry Wt %)	($/ Bushel)	Avg	($/Ton)	(Gallon/ Bu)	($/ Gallon)
Barley	3.3–4.7	Decreasing	55–70	60	48	14.5	55	$2.10–$2.80	$2.50	$104	2.2	$1.14
Oats (hulless)	1.8–2.3	Variable	62–65	63	34	14	60	$1.10–$1.80	$1.60	$94	1.1	$1.45
Sorghum	5.5–8.5	Decreasing	51–70	60	56		70	$1.60–$2.40	$2.00	$71	2.7	$0.74
Wheat	46–53	Variable	35–44	40	60	13.5	72	$2.80–$3.60	$3.25	$108	2.74	$1.19
Corn	69–75	Increasing	130–160	145	56	15	72	$1.80–$2.80	$2.25	$80	2.8	$0.80

Table A-4. Sugar Crop Comparison

Crops	**U.S. Acres Harvested**		**Crop Yield**	**% Sucrose**	**Crop Price**	**Average**	**Ethanol Yield**	**Cost of Ethanol**
	Million Acres	**Trend**	**Ton/Acre**	**Dry Basis**	**$/Ton**	**$/Ton**	**Gallon/Ton**	**$/Gallon**
Sugar Beets	1.2–1.4	Decreasing	20–24	64–70	34–41	37.50	22.1	$1.70
Sugar Cane	0.9–1.0	Decreasing	29–35	70–90	26–30	28.00	16	$1.75

Appendix B: Market Penetration Modeling: The Biomass Scenario Model (BSM)

Most analyses performed to characterize the potential of biofuels technology are static in nature in that they are snapshots of the current market and technology status. But understanding deployment requires another dimension: time. Only in the context of time can one understand the sequence of events behind the deployment of biofuels technology. A dynamic system model to investigate potential market penetration scenarios for cellulosic ethanol is an essential component to understanding the interplay between different areas of the supply chain and investor behavior.

B.1 The Biomass Scenario Model (BSM)[i]

In 2005, the Biomass Program at NREL—working with Dartmouth College and the Natural Resources Defense Council—developed a dynamic systems model to understand the market dynamics associated with deployment of bioethanol technology. That model—the Biomass Scenario Model (BSTM)—has served as a useful prototype for the type of modeling work that will be needed to strategically assess R&D and deployment strategies of DOE's Biomass Program. See Figure B-1 for a simplified schematic of the model.

The model attempts to define the dynamics (i.e., the timing) of building each of the components of the supply chain for a future ethanol industry. The key components of the supply chain are shown along the top of Figure B-2. The model consists of multiple, interrelated "layers" as shown below. The key components of the dynamic framework are:

- The supply chain represents the physical movement of materials starting at the farm and ending in the vehicle utilization of the fuel.
- The infrastructure that supports movement through the supply chain.
- R&D, piloting, technology risk reduction.
- Conversion Plant investment decisions.
- Policies effecting biomass-based fuel production & usage.
- The "external economy," infrastructure development, corn, EtOH and Fuel Markets.

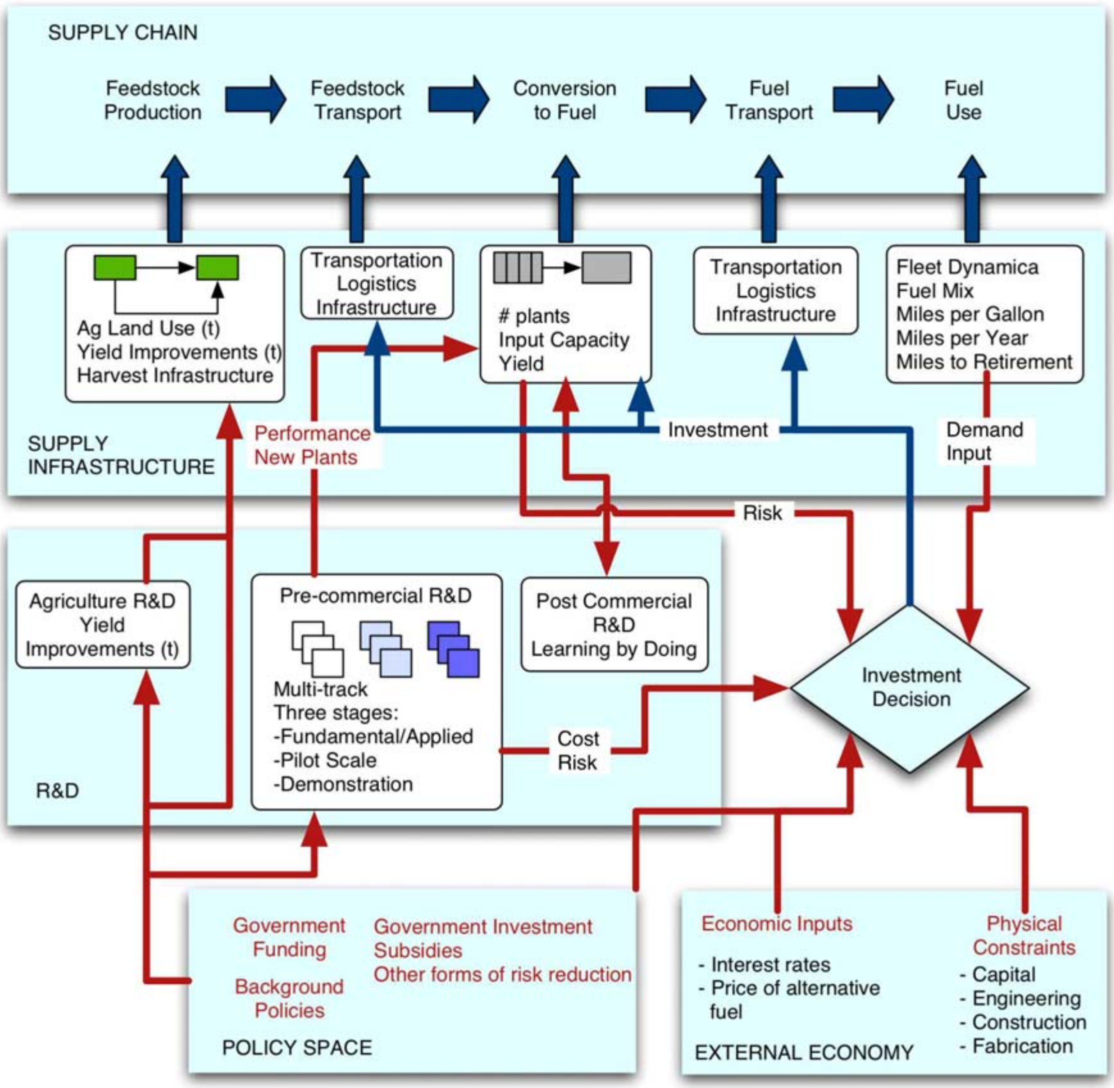


Figure B-1. Schematic of BSM

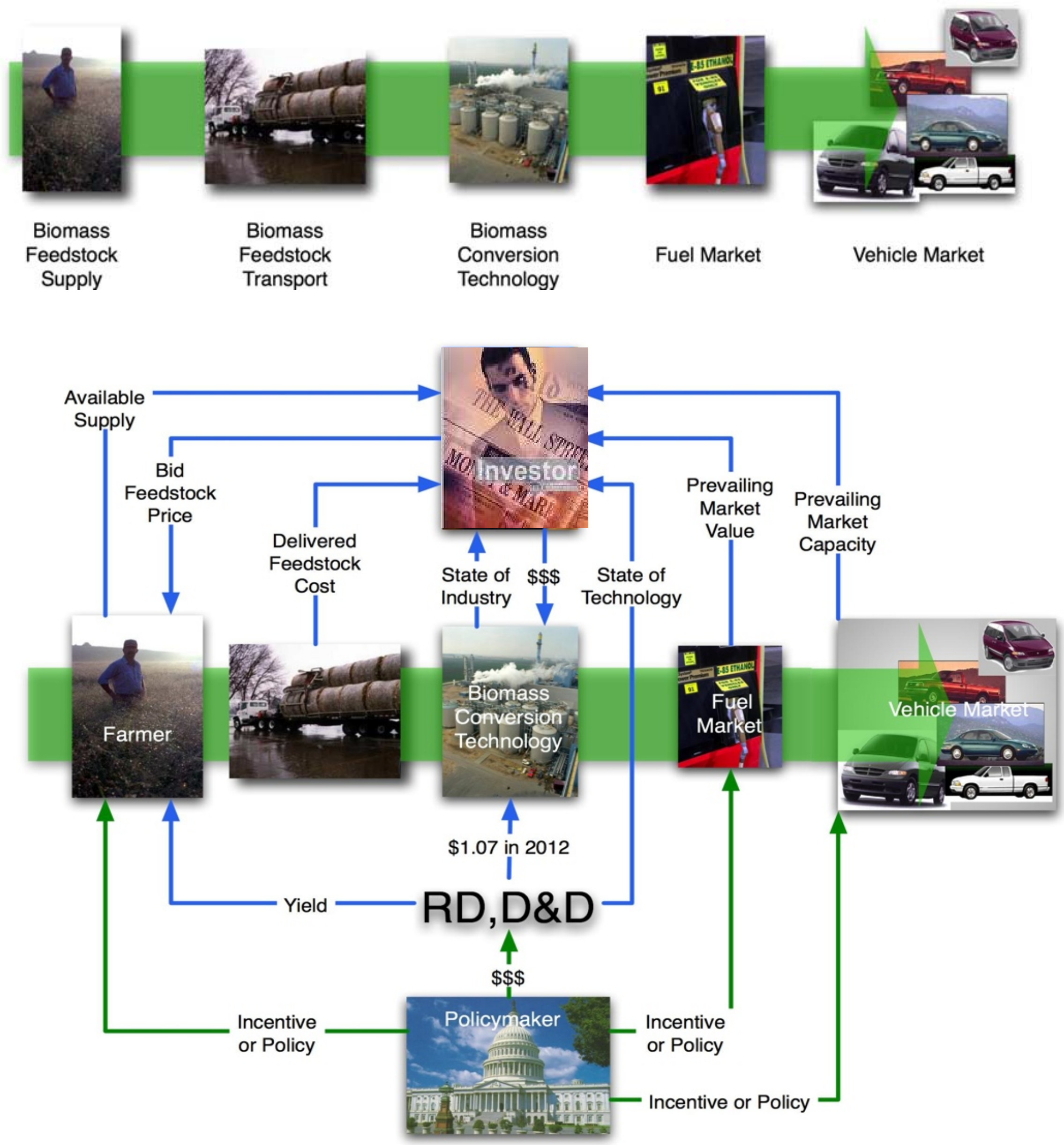


Figure B-2. Supply Chain and BSM Framework

B.2 BSM Model Platform (STELLA™)

There are many software tools and techniques available for assessing and predicting dynamic behavior, with varying degrees of complexity and ease-of-use. After assessing the pros and cons of the various available options, STELLA™ was chosen as the platform for the BSM. This general modeling tool provides a simple visual language for representing different types of dynamic behavior in systems. Its relatively intuitive nature is well suited to the kind of general "what if" scenario building we are interested in doing as we look ahead to understand the possible paths for a new bioindustry. The software translates the elements of ordinary differential equations into relatively intuitive elements.

B.3 The Language of Dynamic Systems

STELLA™ requires modelers to learn the language of dynamic systems. This systems language is used to write a story. It comes with its own set of nouns, verbs and adjectives. Nouns, verbs and adjectives are combined to create descriptive "sentences" that make up parts of the systems story we are trying to tell. A simple sentence in STELLA™'s graphical interface looks like Figure B-3 and detailed in Table B-1.

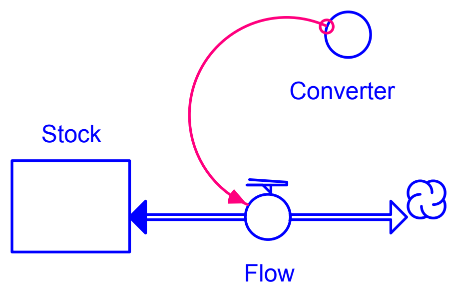


Figure B-3. The Language in STELLA™

Table B-1. Elements of STELLA™ Components

Component	Systems Language Analog	Definition
Noun	Stock	An accumulation of some "thing"
Verb	Flow	A movement into or out of an accumulating stock
Adjectives and Adverbs	Converters	Algebraic statements describing the behavior or logic associated with a flow (adverb) or a stock (adjective)

The modeler develops sentences using this framework to describe and model the behavior of the system. A simple example of this modeling process is as follows:

To describe agricultural land use to support the bioindustry, a sentence is developed as follows and modeled as shown in Figure B-4:

> "*The amount of land dedicated to switchgrass production increases as farmers decide to plant switchgrass and decreases as farmers decide to replace switchgrass fields with other crops*"

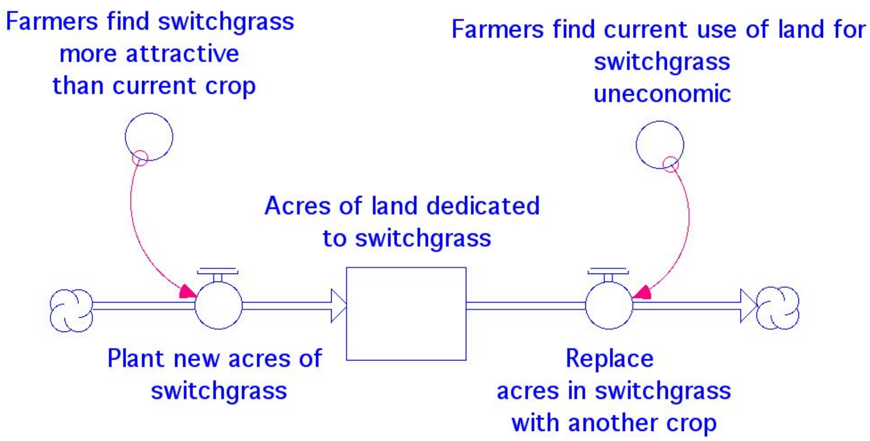


Figure B-4. Example of STELLA™ Language for Biomass Production

As Figure B-5 shows, the STELLA™ modeling tool is used to integrate all aspects of the model. The STELLA™ component is used to focus on the dynamic behavior, and other, more specialized models and sources of information are relayed on for much of the technical and market characterizations that is needed.

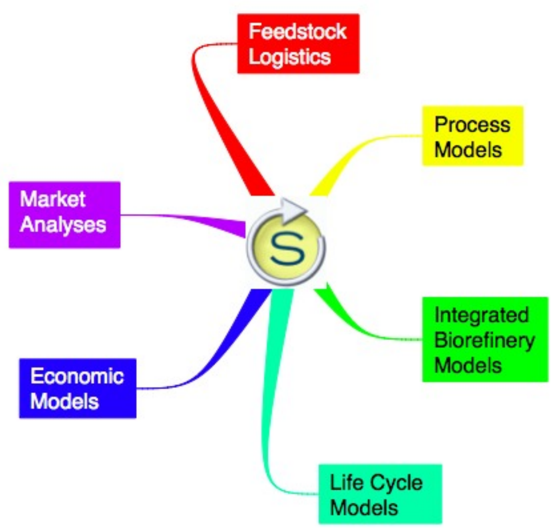


Figure B-5. STELLA™ Model as an Integrating Tool for Other Detailed Biomass Analysis

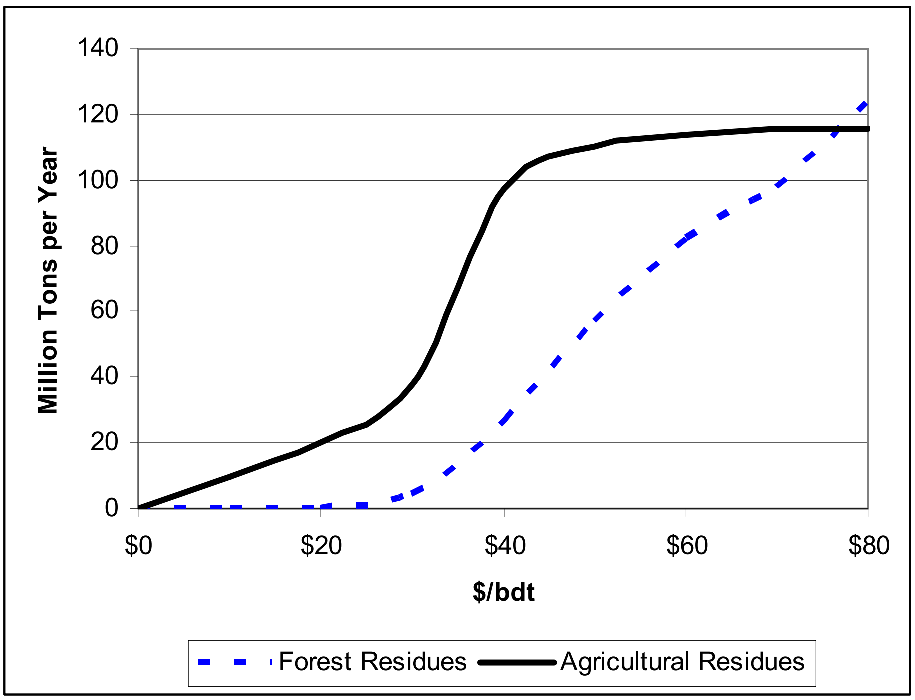
B.4 Detail of Supply Chain Components in the BSM

B.4.1 Biomass Feedstock Supply

The biomass feedstock sections of the BSM describe the relationships of biomass production and land use as they pertain to the bioindustry. Feedstock production modules calculate the potential of biomass that can be used from forest residues, agricultural residues and switchgrass sources.

Agricultural and forest residue availability are calculated as a function of offer price. The annual forest residue availability is fixed and is a function of price only, while the agricultural residues have the ability to grow at the rate of 1% annually for a 25 year period. The 2005 baseline availability for forest and Agricultural residues is shown in the figure below.

Figure B-6. Agricultural and Forest Residue Availability



Switchgrass production is a function of the yield (ton per acre), driven by R&D in the agriculture sector, and the rate in which land is planted in switchgrass. The yield increase that results from R&D is a function of the investment into the various R&D programs. The BSM has a maximum effective investment ceiling of $10-million annually. This means that any amount spent over the ceiling will have no further affect on improving yield. The R&D yield growth rate defined in the model is analogous to historical corn yields. Corn yields grew exponentially for some time before slowing to linear growth over time. Switchgrass production volumes are a sum of the production from land in transition and land established in switchgrass. The land in transition is defined as the product of acreage converting to switchgrass and the yield based on the state of the art agricultural R&D. Production from established land is the product of mature switchgrass and the yield based on actual production.

Land allocated to switchgrass is based on the economic attractiveness to grow and harvest switchgrass for ethanol production. The decision for the farmer is simple; if there is more net profit to be made by planting switchgrass, they will. The BSM controls the growth rate of switchgrass with the following graphical function, where the switchgrass revenue per acre is compared to the revenue of land in other (non-switchgrass) uses. Depending on the ratio, switchgrass is either introduced or replaced at the rate shown on the y-axis in Figure B-7.

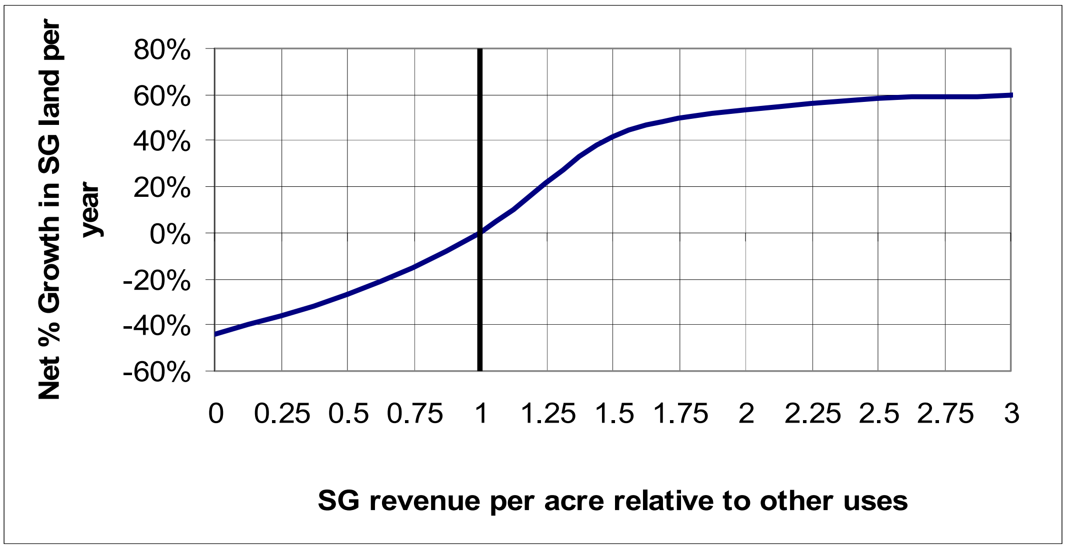


Figure B-7. Rate of Land Movement into Switchgrass

B.4.2 Biomass Transportation

The biomass transportation section of the supply chain calculates the cost of delivering the feedstock from the farm gate to the plant gate. The feedstock price is calculated in two pieces; 1) payment to grower and; 2) transportation cost.

The grower payment in the BSM is not static. Instead, lignocellulosic biomass feedstock costs are determined through a dynamic bidding process in which the investor in a new cellulosic ethanol plant looks at the available biomass inventory to determine if, at current prices, there is enough to support a new processing facility. If not, the investor bids up the market price until the response from the biomass feedstock supply system is sufficient to meet demand.

The cost of transport is usually broken down into two types of costs—fixed and variable (see Table B-2). Fixed costs—expressed in dollars per ton of biomass—are not affected by transport distances. Thus, loading and unloading operations are included here. For simplicity, we also lump annualized capital costs for all equipment in the fixed cost. Variable costs are including all operating costs associated with transportation. In either case, operating costs include labor, maintenance, fuel and oil.

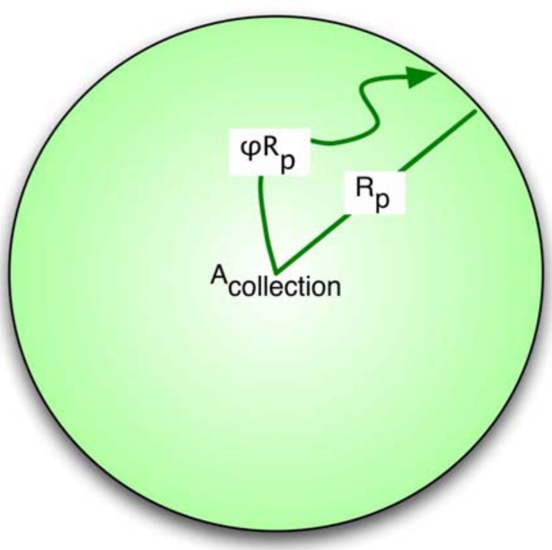
Table B-2. Fixed and Variable Transportation Costs

Type of Cost	Component
Fixed	Loading Operating Costs
	Unloading Operating Costs
	Annualized Capital Costs for Loading Equipment
	Annualized Capital Costs for Transportation Equipment
Variable Costs	Transportation Operating Costs

Cost of transport is expressed simply as:

$$\text{Cost}_{transport} = \text{Cost}_{fixed} + \text{Cost}_{\text{var}\,iable}\text{D}_{\text{p}}$$

Total cost of transportation is expressed in $ per wet ton of biomass. The variable costs are expressed in $ per wet ton-mile, while the fixed costs are expressed in $ per wet-ton. The larger the distance for transport (Dp), the higher the overall cost for delivering the feedstock to the plant. Thus, unlike the capital and operating costs for the conversion facility, feedstock delivery cost actually increases in proportion to the square root of the size of the plant from which biomass is collected. The area of collection is function of yield of biomass per unit area and the percent of surrounding land that has biomass available:



$$A_{collection} = \rho\pi R_p^2$$

$$A_{collection} = C_p d_{online}$$

$$C_p d_{online} = \rho\pi R_p^2$$

Where;

$A_{collection}$ is the area of biomass collection surrounding the plant, which will meet the total annual biomass supply of the facility

R_p is the radial distance of collection around the conversion facility in miles

C_p is the daily biomass throughput of the conversion facility

d_{online} is the number of days per year online

ρ is the density of available biomass in the surrounding area in ton per acre of surrounding land, and is calculated as:

$$\rho = Y_{harvest} f_{biomass} \left[acre/mi^2\right]$$

Figure B-8. Biomass Collection Radius Logic

Where;
$Y_{harvest}$ is the yield of harvestable biomass in dry tons per acre of land which is providing biomass to the facility
$f_{biomass}$ is the fraction of the surrounding land that is actually providing biomass to the conversion facility, and
[acre/mi^2] is a conversion factor of 640 acres per square mile
Solving for the radial collection distance around the plant gives the following:

$$R_p = \sqrt{\frac{C_p d_{online}}{\pi Y_{harvest} f_{biomass} \left[acre / mi^2 \right]}}$$

B.5 Biomass Conversion Plants

The biomass conversion plants section is made up of several modules. In order for the biofuels industry to grow, there must be successful R&D programs to reduce the risk for conversion technology to enter the marketplace. Once the R&D has been proven at the pilot scale, plants may begin to be built at the demonstration, pioneer and finally the full size scale as long as the investors find the market for biofuels production attractive.

B.6 R& D

There are two areas of R&D that must be successful in order to enable the biofuels industry; the area of applied fundamentals and piloting. Analogous to agricultural R&D efforts described earlier, successful R&D in fundamental sciences is a function of the amount of dollars invested. As the amount of effort ($) is increased, the R&D yield (gal/ton) is increases until it reaches its maximum. Similarly, the capital cost growth is lowered as a result of increased effort.

Piloting R&D builds on the R&D yield and capital cost growth reduction accomplished in fundamental R&D. R&D in piloting enables yields to approach those found through fundamental R&D efforts. Once again, the amount of success in piloting is directly related to the funding input. Without piloting, the maximum yield that can be obtained is only 50% of that obtained though fundamental R&D.

B.7 Conversion Facilities

Fundamental R&D and piloting efforts has a direct impact on plant performance. Plants are designed based on feedstock availability and design yield (gal/ton). Plant performance is also influenced by the overall experience of the industry, which goes through a learning curve until the yields reach their maximums. The BSM assumes that the cellulosic ethanol industry reaches maturity and maximum yields when the average plant capacity is at 600 million gallons annually. The demand for ethanol coupled with the increased plant yield due to industrial maturation dictate the growth of the industry by new plants being constructed. Demonstration, pioneer and full scale plants are constructed depending on performance. Each plant goes through a design and construction, start up and online phase where costs and yields are determined separately. Utilizing the number of plants coming on line and operating, average yield and utilization allows the BSM to calculate the industry output in gallons and feedstock requirements. If the feedstock availability is less than the plant requirements, the industry will reduce its growth rate to match the available feedstock supply.

B.8 Investment

Investor attractiveness to build plants depends on the cost of cellulosic ethanol production, including rate of return on investment. Other factors, such as the demand and competitiveness of the marketplace are also crucial factors, as are any government subsidies for biomass or fuel production.

Capital costs are calculated for each scale of plant in the BSM. Using experience at previous scales allows for capital cost growth reductions as the size of plants increase. Reductions in capital can also be realized through co-location options for the first facilities, before stand-alone Greenfield plants become economically viable. As the industry ramps up from demonstration to pioneer to full scale facilities, the capital growth factor at each stage is dependent on the accumulated experience at previous scales.

Depending on the scale of the plant and the prior scale experience, investors will require a certain rate of return on their investment. The BSM models three types of investor behavior; conservative, moderate and aggressive, along with a mature industry rate of return and a new industry risk factor to determine the required rate of return on plants. To reduce risk, investors (depending on what type) require experience at prior scales before lowering the required rate of return on the next larger scale. For demonstration plants, the BSM only requires a 2% rate of return, assuming that demonstration plants are an investment in proving out technology and the investor is willing to accept a lower return as a trade off for return on full scale plants.

Finally, total plant costs can be calculated by adding the cost of capital + taxes + loan. The BSM utilizes standard financial calculations to calculate the capital recovery factor, annual return before and after taxes and annual loan payments.

B.8.1 Fuel market

Penetration of ethanol from cellulosic feedstocks finally is a function of the marketplace. The price of corn and its effect on the corn ethanol market, along with the current gasoline market. Costs have a major influence on the rate in which cellulosic ethanol can penetrate into the fuels market. The price of corn is determined from a relationship of price to its supply demand ratio, which is a function of demand for other uses to the total production minus corn being used for ethanol. Corn production is calculated as the yield per acre times the number of planted acres. The BSM models the yield to increase linearly at a rate of 1% annually for 25 years from the current 2006 level of 160bu/acre. Other traditional non-ethanol demand for whole corn increases annually at its historic rate of 0.8%. Finally, demand for corn for ethanol production is calculated from the corn ethanol plant capacity and plant yields.

The price for corn ethanol is calculated based on specified capital, operating, and corn costs minus DDG revenues and any existing subsidies. The attractiveness to build corn ethanol plants is based on the competing prices of cellulosic ethanol and gasoline. The attractiveness is a ratio of the corn ethanol price to the lower of either the cellulosic ethanol or gasoline price. The BSM uses an attractiveness factor along with a maximum growth rate to determine the corn ethanol growth and total corn ethanol industry capacity.

The fuel marketplace for ethanol is based on various future oil price scenarios. At low volumes, the value of ethanol is enhanced due to its value as an oxygenate and octane enhancer. However, that advantage disappears at an ethanol production rate of around 8-billion gallons per year, when ethanol begins to enter the market more as a primary fuel.

B.8.2 Vehicle Market

The vehicle market in the BSM is designed to calculate the potential demand for ethanol. In the BSM, there are two future vehicle scenarios; business as usual which has a very slow growth rate of E-85 vehicles and in essence inhibits ethanol growth due to lack of demand, and the Union of Concerned Scientists (UCS) estimates, where the influx of E-85 vehicle takes place at an accelerated rate and thereby allows for unconstrained ethanol industry growth from a demand perspective. The UCS estimates were used for all the runs in the 30x30scenario, so that there would not be a demand constraint.

The BSM tracks the number of vehicle and the efficiency of each vehicle type. Using the number of vehicles and efficiency of the fleets, the BSM calculates the potential ethanol demand for total, E-85 and E-10 vehicles. The demand is then compared to the total production to measure the attractiveness for investors to build additional plants.

Table B-3 below list the important assumptions made in the BSM as well as sources for information that went into the model.

TableB-3. Assumptions Used in Modeling the BSM

Supply Chain Element	Assumptions
Biomass Production	Ag residues supply per ORNL 2000, Biomass Feedstock Supply Curves U. Tennessee POLYSYS land competition model for switchgrass on prime cropland Switchgrass yield of 5 tons per acre rising 1.5% per year to 13 tons per acre in 2050 Corn at $1.90 per bushel with small increase as function of demand No arbitrary limit on corn supply for ethanol Only change in agricultural policy is allowance for energy crop harvesting on CRP land
Biomass Distribution	Truck delivery up to 50 miles to plant
Biomass Conversion to Biofuels	$1.07 per gallon ethanol nominal price target in 2012 at pilot scale Three year lag from pilot to full scale Maximum plant build-out 5 billion gallons per year (historical gasoline data) 5,000 ton biomass per day commercial bioethanol plants Investor finance assumptions: 30% ROI for new technology declining to 10% ROI as industry experience reaches maturity; Debt: equity ratio of 40/60; Debt finance assumption of 25% capital cost growth for new plant, declining to zero for mature industry or set to zero for loan guarantee scenarios.
Biofuels Distribution	No modeling done (assumes infrastructure development not rate-limiting)
End Use Market	Two vehicle scenarios: 1) business-as-usual rate of FFV introduction 2) aggressive FFV introduction per Union of Concerned Scientists vehicle fleet model Fuel market based on AEO 2006 Oil Projections ORNL refinery model analysis to predict ethanol blending value as a function of demand

Appendix C: Assessment of Uncertainty and Risk for Biomass Conversion Technologies

The goal of risk assessment is to investigate factors that can affect the commercial success of processes and technologies and then to plan for them. For biomass conversion, risk assessment can be applied to the development of biorefinery processes that will provide the ethanol needed to replace 30% of 2004 U.S. motor gasoline demand by 2030.

Risk assessment translates uncertainty into a risk rating by incorporating qualitative judgments. Risk assessment is not a single activity but rather encompasses a range of activities that require a range of tools and methods.

There are various aspects of risk assessment, but a core component is uncertainty analysis. Types of uncertainty include:

- **Financial uncertainty**
  How do the financial assumptions affect the estimate of production costs? Can better financial assumptions offset technology targets that have not been fully met?
- **Market uncertainty**
  If all technology and cost targets are met, will the technologies be accepted in the marketplace and commercialized?
- **Process uncertainty**
  If pieces of process technology (such as yields) are not obtained, how will it affect production costs? What if some pieces are better than expected? How much can this offset pieces that are not as good as expected?

Other aspects of risk assessment are more difficult to quantify. These include:

- **R&D risk**
  What is the ability to achieve R&D targets? On what does success depend? Will increased funding necessarily result in successful R&D? Are there differences in the outcomes of R&D funded by government and private industry?
- **Deployment risk**
  What is the likely process configuration to provide a positive internal rate of return? Can processes be guaranteed? How likely is industry growth?
- **External factors**
  What other factors (such as fuel and market turns and policymaking) could play a part in development and deployment?

Methodology can also be difficult to determine. Difficulties include:

- **Using past experience**
  Can historical data for similar industries be used to judge this industry? Have underlying conditions changed so that analogies are no longer valid? How are the opinions of experts incorporated—especially when those opinions are in opposition to each another?

- **Developing useful results**
  Is this a high- or low-risk venture? How does it compare with other avenues? What is its ranking on a scale with other options?

C.1 Uncertainty Analysis

The first step of a risk assessment is to identify the process aspects that can be quantified.

Process and financial uncertainty are relatively straightforward quantitative measures. For these, a single-value uncertainty interval analysis can be performed. This analysis involves:

- Estimating the range in which a process or financial variable may occur
- Calculating the cost effect at each extreme
- Holding all other variables the same as the benchmark value.

A more sophisticated analysis involves adjusting multiple variables simultaneously while taking into account the probability of a variable having a certain value. This forms the basis of Monte Carlo analyses. For these analyses, one can calculate not only the range of costs possible but also the costs that are most probable. This type of analysis can uncover interdependencies among process and financial variables, but the accuracy is dependent on how accurately one characterizes the probability of the input values. The validity of a Monte Carlo analysis is also dependent on a robust and mature model to combine the effects of variables. A model that is not robust can give misleading results. For example, the models for the biochemical conversion operations are more mature than the models for feedstock delivery systems and thermochemical conversion operations. A Monte Carlo analysis of these processes would not give as-accurate results. The same situation applies for the advanced technology process scenarios. More process detail is needed before a multivariate analysis would be useful.

C.1.1 Uncertainty Analysis for $1.07/Gallon Target Technologies

Uncertainty analysis was performed on the feedstock assembly, biochemical conversion processes, and thermochemical conversion processes that make up the $1.07/gallon target cases. The results are loosely grouped into three types of uncertainty:

- **Financial uncertainty, including capital and operating costs and investment assumptions**
  Equipment, supplies, and loans make up this type of uncertainty. However, by using experts such as vendors and engineering/construction firms, information can be gathered to reduce equipment uncertainty. Chemical and other operating expenses can also be determined with relative ease. Investment assumptions are the most difficult to determine but the easiest to evaluate via uncertainty analysis.

Here, ethanol production costs have been expressed as MESPs. An MESP is the result of a specific financial scenario that ties together levels and types of technologies, operating and installed capital costs, and the time-value of money. The particular financial scenario for an MESP attempts to be an average of debt versus equity financing and a reasonable internal rate of return. The MESP provides a mechanism for comparing one type of technology with another, especially if they have different relative operating and capital costs.

- **Market uncertainty, including product values and plant size**
  Product value and volume data are relatively easy to obtain; however, the introduction of a new or replacement product into an established market affects the market in uncertain ways. It can reduce or inflate value and change the volume of both demand and supply.

  Because co-products will be important to the economic health of individual processing plants, it is important that plant developers look closely at their effects. However, the cost analyses presented here represent industry averages. In this case, significant co-product credits are justified only if:

  - The market for the co-product is on the same order as the fuels market (such as co-produced electricity)
  - The amount of co-product is a fraction of that material's market (and the production of that co-product by all processing plants will not swamp the market).

  Significant co-product credits can be justified only in near-term scenarios. In the near term, a small number of processing plants are expected to produce these co-products. These plants will ensure that they can sell the co-product into the market at a price approaching market value.

  Overall ethanol market acceptance has been estimated in the past using market models (such as MARKAL and the National Energy Modeling System). These models attempt to answer questions about how competing energy sources and technologies will be used to supply the needs of the marketplace.

  Plant size is dictated by supply and demand economics. There is an economy-of-scale effect that, when taken advantage of, significantly reduces the cost of capital.

- **Process uncertainty, including research targets and other process parameters**
  The cost implications of missing, hitting, or exceeding a target or set of targets are easily seen with process uncertainty analysis. Combinations of sensitivity analysis can provide several ways to achieve the same cost target, which reduces the overall risk of the process. Quantifying the relative cost savings of process improvements allows work to be directed to the most cost-effective R&D.

Newer transition models attempt to combine the effects of market "pull," operating cost "push," policy, and financial factors. These models are the most complete at incorporating multiple aspects of uncertainty.

These are not exhaustive collections of items of uncertainty but rather those thought *a priori* to have the greatest effects. However, analysis shows that not all of these items have as large of an effect as might be expected.

C.1.1.1 Feedstock Assembly

Feedstock assembly core R&D involves developing and applying technologies that address the barriers identified in the *Roadmap for Agricultural Biomass Feedstock Supply in the United States* (Cushman 2003). Overcoming these barriers is necessary for the achievement of the interim (2012) tonnage, cost, and regional accessibility targets. For R&D purposes, the barriers have been grouped into harvest and collection, storage, pre-processing, and transportation and handling unit operations. Figure C-1 summarizes the technical parameters and their feedstock assembly unit operations.

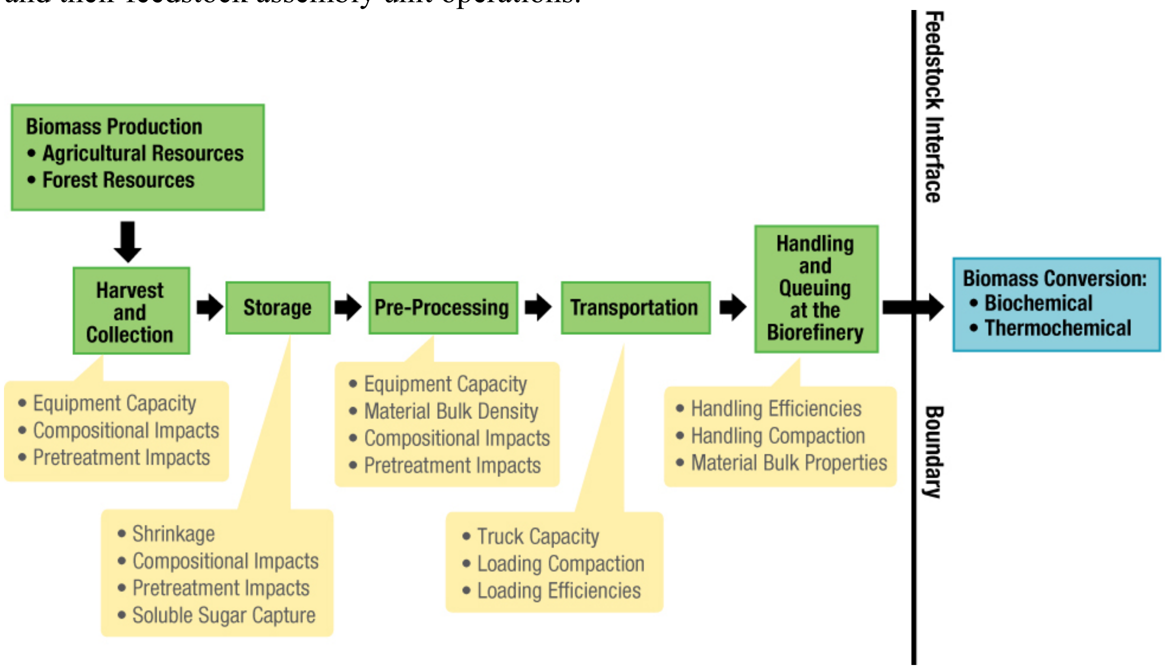


Figure C-1. Technical Parameters Associated with Feedstock Assembly System Unit Operations

The delivered cost and quality of biomass feedstocks is dependent on market and policy drivers as well as technical parameters. The sensitivity and risk associated with market and policy drivers are handled at the industry scale with appropriate models. However, the implied risks associated with feedstock assembly core R&D and analysis are assessed by applying a single-value uncertainty interval analysis to feedstock technical parameters. The results of this analysis are shown in figures C-2 and C-3.

To perform this analysis, a model capable of quantitatively determining the integrated and individual costs of feedstock assembly and pre-processing operations must exist. This model must then be used to evaluate the high, mid, and low ranges of each technical parameter to provide the relative sensitivity of these parameters to the feedstock assembly and pre-processing system.

The dry feedstock assembly system is the most mature in terms of engineering data and assembly system models that incorporate the R&D needs of the conversion processes. These data and models were used to determine the range of sensitivity of the dry feedstock technical parameters as well as the relative costs associated with different unit operations and cross-cutting costs.

The tornado chart in Figure C-2 presents the ranges of sensitivity for each of these parameters. The ranges are based on the 2012 delivered feedstock target of $35/dry ton and illustrate the potential of each parameter to affect the overall assembly system cost through engineering and quality impacts. The chart is split into three regions: (1) specific research technical parameters that directly affect the cost and quality of delivered feedstocks, (2) unit operations that make up the assembly system, and (3) variable costs that cross-cut all assembly system operations. The technical parameters are the primary focus of the risk analysis because their effect will determine how and why the cost targets are met. The other regions show the relative effects the technical parameters have on the assembly system as a whole.

The ranking of each parameter with respect to another implies some degree of R&D risk. Those parameters with large cost ranges have a greater potential to affect the 2012 targets (positively and negatively). However, inherent with the single-value analysis approach is the inability to identify the interdependence of parameters. Although a Monte Carlo analysis could determine this interdependency, the feedstock assembly system models are too immature to provide the input ranges required. Thus, Figure C-2 will assist in identifying and directing R&D based on relative potential but cannot be used to determine the effect of changing a single parameter on other parameters. Nevertheless, it is expected, based on the nature of each feedstock assembly unit operation, that synergistic credits or debits will be realized.

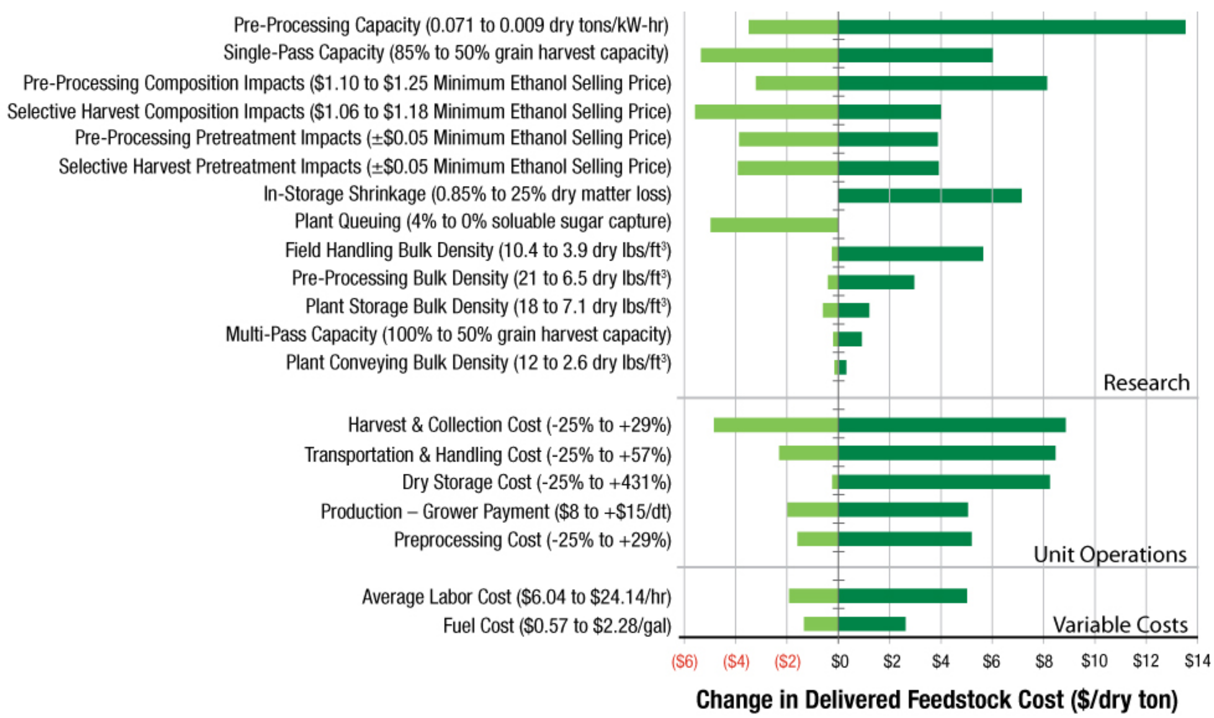


Figure C-2. Sensitivity Analysis of Technical and Logistical Parameters in the Dry Feedstock Assembly $35/dry ton Case

Figure C-3 shows the sensitivity of R&D technical parameters specific to a wet feedstock assembly system. As before, each parameter is based on the 2012 delivered feedstock target of $35/dry ton and illustrates a relative effect on assembly system costs and feedstock qualities. Unique to the wet feedstock type is its potential to use in-storage pre-processing technologies to significantly affect feedstock cost and quality. Specifically, the free sugar capture and reduced pretreatment severity parameters have the potential to offset much of the storage, pre-processing, and transportation costs (which are higher than the respective dry system costs because of the water content of the feedstock).

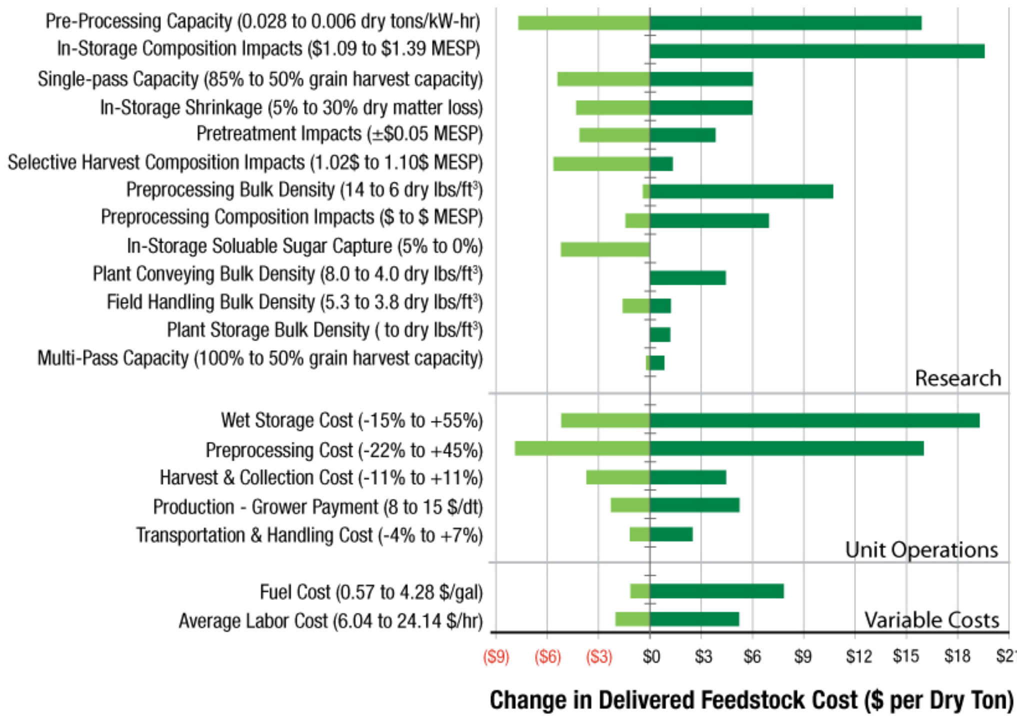


Figure C-3. Sensitivity Analysis of Technical and Logistical Parameters in the Wet Feedstock Assembly $35/dry ton Case

C.1.1.2 Biochemical Conversion Technologies

Sensitivity analysis of biochemical processes has been a cornerstone of R&D in the OBP and, prior to that, EERE biofuels programs. These analyses have provided information about the most cost-sensitive parameters of the technology. In recent years, groupings of parameters have identified “barrier areas” in the conversion process. These have proved useful in the quantification of the challenge of biomass processing. Figure C-4 highlights these challenges.

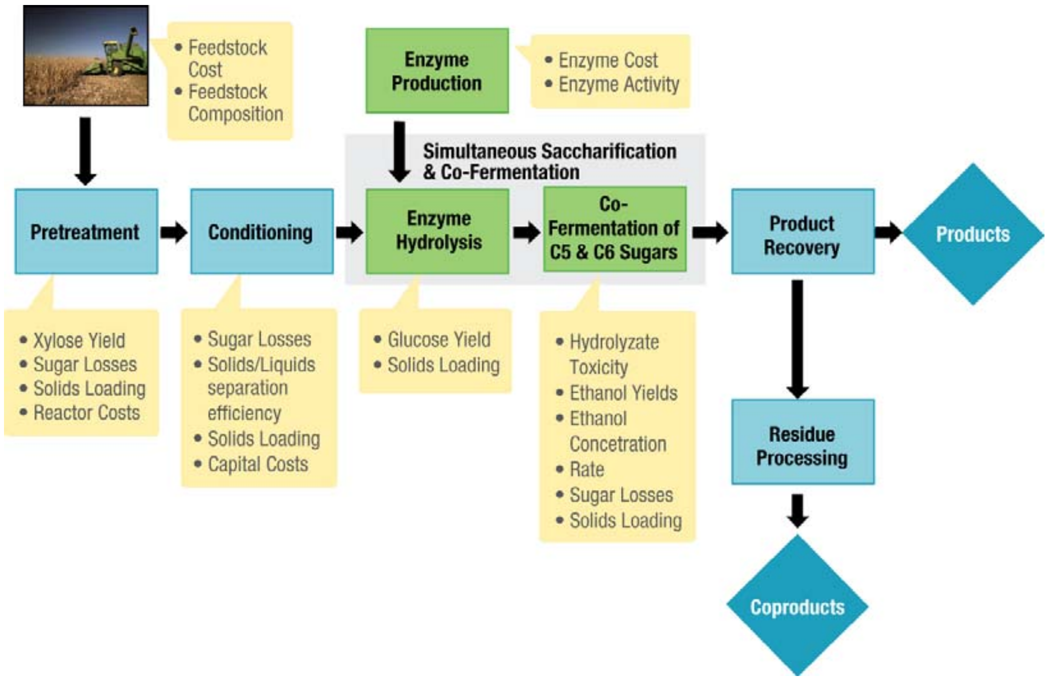


Figure C-4. Barrier Areas for the Biochemical Ethanol Process

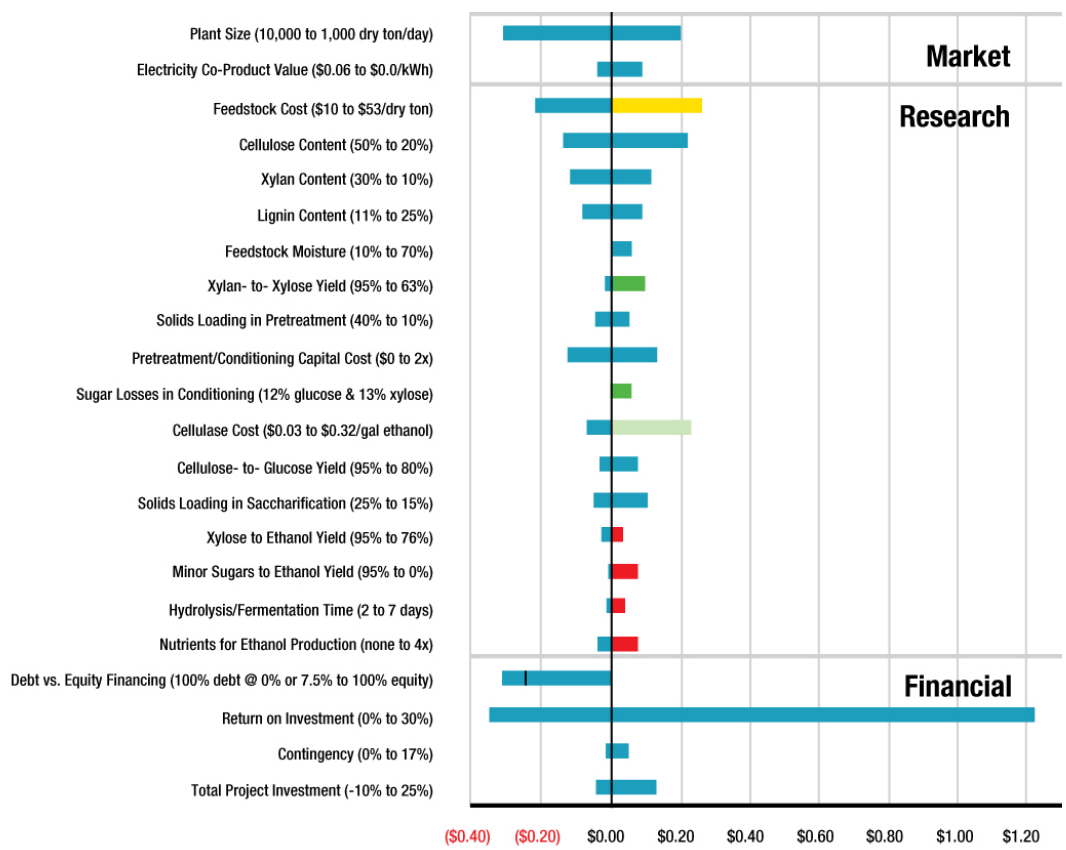


Figure C-5. Single-point Sensitivity Analysis of Process Parameters in the Biochemical Conversion $1.07/gallon Target Case

Many market factors are possible, but the two selected, plant size and electricity value, demonstrate the range of effect. Plant size, because of economies of scale for capital equipment, has a large effect. It is determined by factors such as feed availability and cost, market demand, and technology level (e.g., pilot or demonstration). However, the electricity credit has a small effect on production costs.

Of the financial parameters evaluated, ROI has the greatest effect. A higher required ROI can result from higher risk perception by financiers. This can be reduced by piloting and demonstrating facilities to prove the technology at larger and larger scales prior to building a commercial plant. Getting a no- or low-cost loan through a guarantee program can reduce the financial burden of capital investment, especially when the loan is lower than the hurdle rate required by equity holders.

However, of most interest to the R&D program is the effect of uncertainty in the technology. Feedstock cost and composition have significant effects on production costs. Moisture that does not affect solid loading in the process appears to have a minor effect. As higher-solids processing is achieved, feedstock moisture will begin to drive process loadings. Yields, whether in pretreatment or fermentation, can have a large effect on cost. For the ranges studied, which were developed from state-of-technology and target values, pretreatment yields of xylose were the largest factor, in part because larger pretreatment yields ultimately lead to larger ethanol yields.

Table C-1 shows abbreviated process targets and is color-coded to Figure C-5 by barrier area. Of the process targets that have not yet been met, feedstock and enzyme cost have the largest effects. Pretreatment yields of xylose and fermentation yields of all sugars combined also have large effects on the production cost of ethanol. Conversely, some achieved targets, such as solids loading in saccharification, could be improved for cost savings or to offset problematic targets. Other parameters, such as capital costs and feedstock composition, are, at best, identified as areas of uncertainty that must be tracked and, if possible, better quantified as the process is developed.

	2005 Post Enzyme-Subcontract	2007	2009	2011	2012 Market Target	Change to MESP ($/gal)
Minimum Ethanol Selling Price	$2.26				$1.07	
Installed Capital per Annual Gallon	$3.04				1.85	
Yield (Gallon/dry ton)	65				90	
Feedstock						
Feedstock Cost ($/dry ton)	$53				$35	$0.26
Pretreatment						
Solids Loading (wt%)	30%	30%	30%	30%	30%	
Xylan to Xylose	63%	68%	77%	86%	90%	$0.10
Xylan to Degradation Products	13%	12%	9%	6%	5%	
Conditioning						
Xylose Sugar Loss	13%	11%	7%	2%	0%	
Glucose Sugar Loss	12%	10%	6%	2%	0%	
Enzymes						
Enzyme Contribution ($/gal EtOH)	$0.32	$0.32	$0.32	$0.10	$0.10	$0.23
Saccharification & Fermentation						
Total Solids Loading (wt%)	20%	20%	20%	20%	20%	
Combined Saccharification & Fermentation Time (d)	7	7	6	3	3	$0.04
Overall Cellulose to Ethanol	86%	86%	86%	86%	86%	
Xylose to Ethanol	76%	76%	80%	80%	85%	$0.03
Minor Sugars to Ethanol	0%	40%	40%	80%	85%	

Table C-1. Possible Interim Targets to $1.07/Gallon Ethanol for Stover

Combining the results of single-point sensitivities with the area results in Figure C-6 provides a snapshot of overall process challenges and areas in which R&D may be lagging.

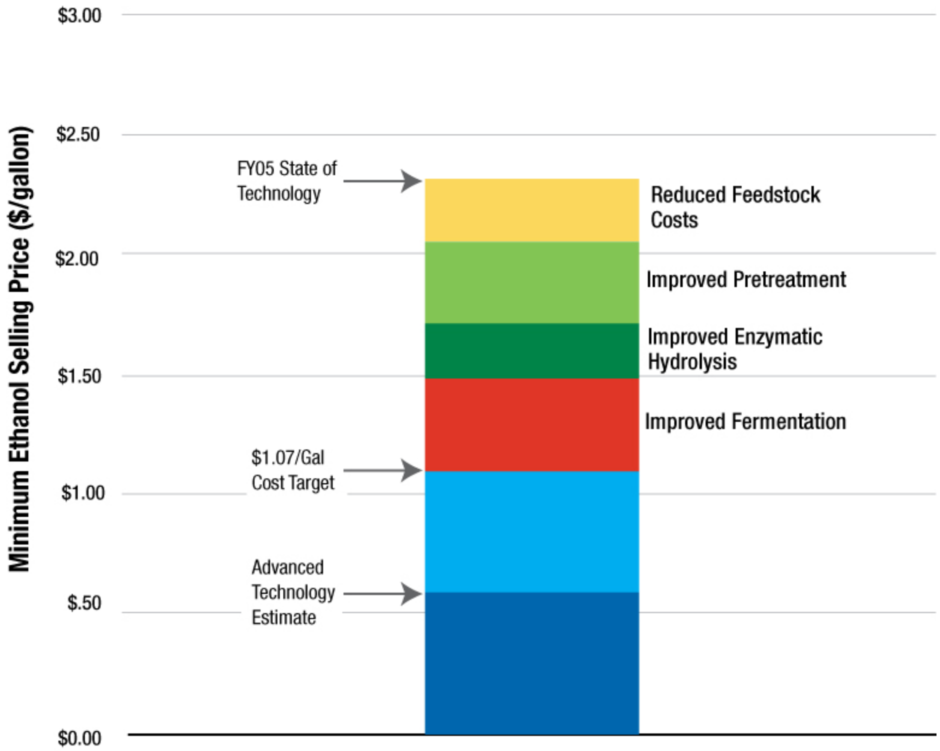


Figure C-6. Combined Sensitivity Analysis Provides Barrier Area Cost Effects

Monte Carlo analysis was used to evaluate the likely production cost of feedstock and process yield variations. Figure C-7 shows the range of production costs possible and the likely values. Feedstock variation had a larger effect on production cost than process yield for the ranges studied.

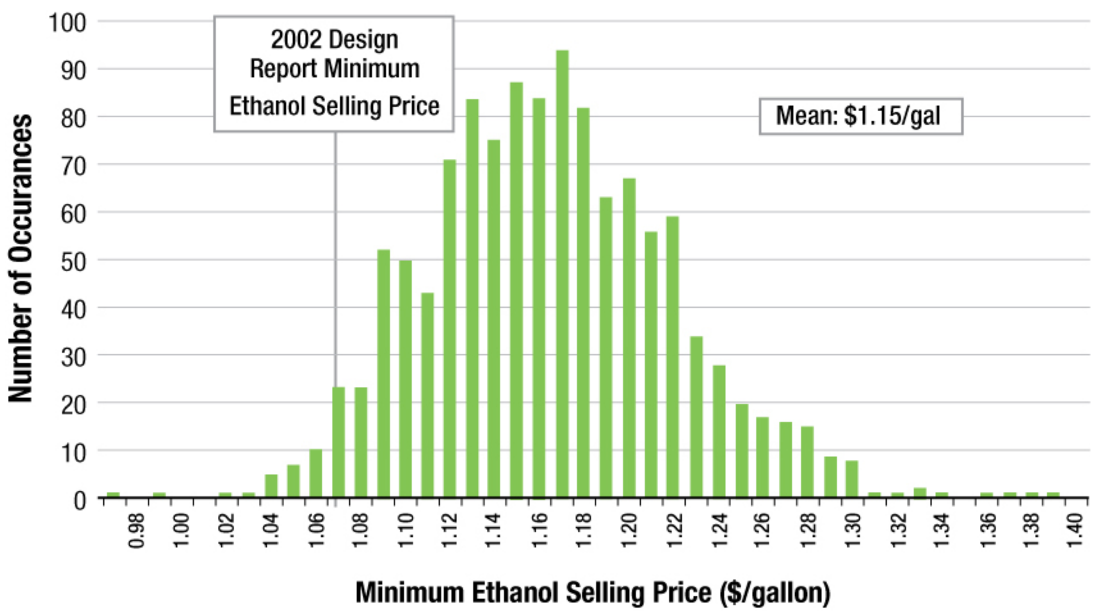


Figure C-7. Monte Carlo Analysis of Feedstock Composition and Yield Uncertainties

C.1.1.3 Thermochemical Conversion Technologies

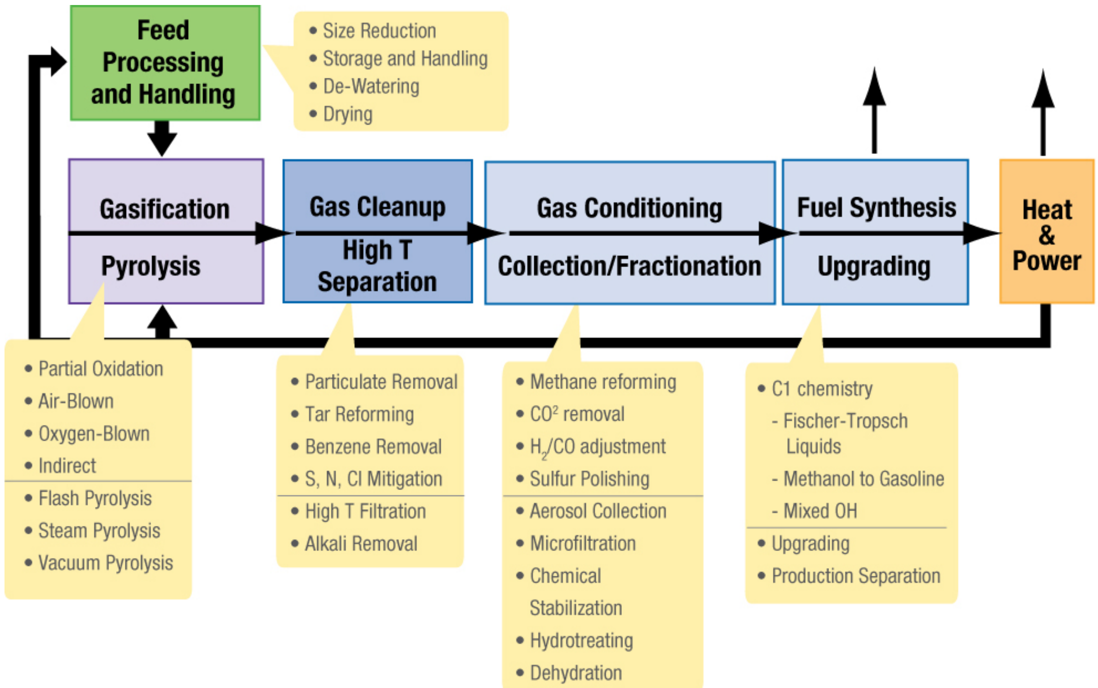


Figure C-8. Barrier Areas for the Thermochemical Ethanol Process

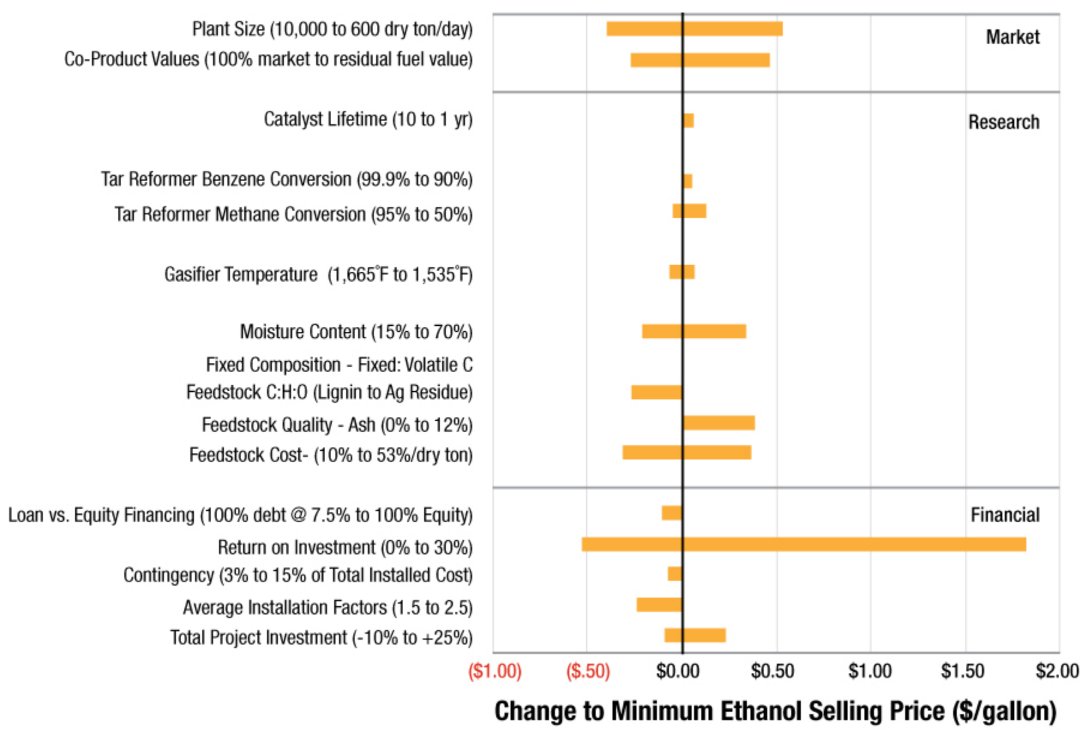


Figure C-9. Sensitivity Analysis of Process Parameters in the Thermochemical Conversion $1.07/gallon Target Case

Figure C-9 depicts the results of uncertainty analysis of the thermochemical conversion process. The market and financial uncertainties are essentially the same as those explored for the biochemical process. The research items are applicable to thermochemical technology and, therefore, are different.

The market (plant size and value of co-products) and financial (required ROI) factors have large effects on production costs. The benchmark plant size was established as 2,000 dry tonnes/day. For a commercial plant, it will be determined by factors such as feed availability and cost, market demand, and the level of technology (e.g., pilot or demonstration). In general, the larger the plant, the lower the capital costs on a unit-produced basis (per gallon of ethanol).

For the thermochemical process, the co-product credit for higher alcohols has a significant effect on process economics. If higher alcohols can be sold in the chemical market, then they will have a value 3–4 times greater than their fuel value ($3.70–$4.20/gallon). This seems reasonable for the first few processing plants or if the amount is small compared with the total market (such as the case for n-butanol). The alternate use for these alcohols is, at worst, as a non-spec fuel (such as residual fuel oil); this would set their value at about 80% of that for gasoline.

A positive characteristic of the thermochemical process is its relative insensitivity to feedstock composition. High-carbohydrate feedstocks (such as wood and corn stover) process at essentially the same cost. Low-carbohydrate feedstocks (such as lignin residues) should give good yields at nearly the same cost. Indeed, low-carbohydrate feedstocks may give higher yields because of their higher heating values and lower oxygen contents.

The process uncertainty results can aid in qualitative risk assessment based on feedstock characteristics. For example, feedstock moisture content has a smaller effect on biochemical processing costs (because water is added anyway) than on thermochemical processing costs (because the feedstock is dried before gasifying). However, actual carbohydrate composition of feedstock has a much larger effect on biochemical processing costs (because only the carbohydrates are converted to ethanol) than on those of thermochemical processing.

C.1.2 Advanced Technology Scenarios

Both process uncertainty and risk assessment of the 2030 scenarios are tenuous at best because there is not enough information to do useful process uncertainty analysis. Production yields and costs are based on estimates of what the technology might look like. The best assessment is to consider the large drivers of advanced technology development.

The overall picture of the advanced technology must consider:

- **Feedstock cost versus process cost**
  The highest-cost component in a mature process is feedstock. There is then a trade-off of how low processing costs should be viewed. Will the process produce an inexpensive fuel from a cheap feedstock? Will the process be able to economically produce a fuel using a larger range of more expensive feedstocks?
- **Future technology advances**
  Will existing technology be able to incorporate high-tech advances (such as would be

provided from systems biology and GTL)? Or will the facility need to completely re-invent to incorporate this?

- **Similar external factors as for near-term technology deployment** (such as emphasis of funding sources, competing fuel prices, and public policy).

C.2 Risk Assessment

The next step is to translate, via qualitative methods, the results of uncertainty analysis into a risk assessment of the R&D and deployment paths envisioned to meet the $1.07/gallon target.

C.2.1 Translating Process Uncertainty into R&D Risk

Process uncertainty analyses can help drive the qualitative assessment toward determining the likelihood of achieving targets by identifying:

- High- and low-risk activities (revolutionary and evolutionary)
- The most probable R&D scenario
- Uncertainty in translation to other feedstocks
- Uncertainty in translation to other scales.

There are many risk assessment methods. Most of them are subjective or qualitative. A review of the most applicable is performed, and one, or possibly a mix, is employed. At best, risk assessment is semi-qualitative when coupled with uncertainty analysis to provide some quantitative information. Coupling that information with expert opinion on likelihood of success and historical information is probably the best choice. For the first cut, identifying the risk as high or low provides significant information. Alternatively, classifying the R&D path a set of known activities or completely new activities may enable clarification of which parts are truly revolutionary or evolutionary (Roussel 1983).

The best use of risk assessment results is to mitigate risk via strategies. Several strategies are already being used at some level in the biomass R&D community. A few examples from biomass and other technology communities include:

- **Develop multiple conversion technologies and pathways.**
  Combined scenarios help reduce the effects of failing to meet targets in one platform by achieving successes in another. For example, one of the technology risks in the biochemical conversion process is the conversion of C5 sugars to ethanol. The risk of not converting these sugars biochemically is reduced if a thermochemical conversion process is integrated with the biochemical conversion process. C5 sugars that are not converted biochemically can still be converted thermochemically by routing the waste syrups through the gasifier.

- **Encourage the development of "open source technology."**
  Advocating open sharing of technology improvements, analogous to the computer industry, would make certain discoveries available to all. This would allow research groups to minimize redundant areas of research and speed the overall development of new technologies. The sharing of research results would speed the implementation of

- **Use what is learned on previous feeds to jumpstart new feedstocks of similar type or classification.**
- **Plan for both pilot and demonstration projects.**
  This reduces costs in two ways. First, it reduces process uncertainty and minimizes the over-design of equipment. Second, and perhaps more importantly, it provides demonstrations near scale so the required ROI can be reduced, which lowers financial cost (which has been shown to be a significant portion of the overall cost of producing ethanol).

C.2.2 Translating Process Uncertainty into Deployment Risk

Even with the best R&D plans, there are deployment risks for new technology. Costs invariably are higher for the first plants because of unforeseen difficulties at the commercial scale. A methodology for estimating cost overruns of pioneer plants, outlined in the 1981 Rand Report, was applied to the biochemical process by Wallace (2003). The analysis showed that one of the key areas that drives costs above what are expected is the number of new (unproved at the commercial scale) steps in an overall process.

Near-scale demonstrations are essential to reducing deployment risk. The more processes that are demonstrated near scale, the lower their expected cost is at full scale. Near-scale demonstration also suggests ways to simplify the overall process. The number of actual processing steps is another key area for unexpected cost growth in a pioneer processing facility.

C.2.3 External Factors

External factors that are expected to play a part in the deployment and possibly development of technology include:

- **Private industry**
  Private industry is less likely to share technology with competitors. This will potentially slow the implementation of new technology.
- **Fuel prices**
  If the price of petroleum-derived fuels remains high, there will be less pressure to reduce the production costs of alternative fuels. This may speed up the time frame in which alternative fuels become competitive and widely available.
- **Policy**
  Government policy—including loan guarantees, solicitations, incentives, and taxes—will affect the outcome of development and deployment activities.

Appendix D: Feedstocks Technology R&D

Some of the biggest unanswered questions related to the deployment of cellulosic ethanol biorefineries involve feedstocks. The joint U.S. Department of Energy and U.S. Department of Agriculture "Billion Ton" study (Perlack et al. 2005) identified a domestic cellulosic feedstock resource potential sufficient to displace more than 30% of U.S. 2004 finished motor gasoline demand. However, these questions—e.g., "How can biomass be delivered cost effectively and sustainably to biorefineries?" and "How much biomass is available at what cost?"—represent significant barriers to the 2012 ethanol cost target of $1.07/gallon and the 2030 goal of 30% fuel displacement.

The 2030 goal of 60 billion gallons of ethanol will require the production of 40–45 billion gallons from cellulosic feedstocks, assuming 15–20 billion gallons will be produced from starch feedstock resources. This quantity of cellulosic ethanol will require an estimated 500 million dry tons of biomass. Although the goal of producing, supplying, and converting 500 million dry tons of cellulosic biomass is important, it is also useful to have an intermediate target that:

- Represents a realistic near-future biomass demand
- Includes every major type of cellulosic feedstock
- Enables feedstock at a price that allows the resulting ethanol to be competitive in the near-future transportation fuels market
- Can be described and achieved with technology currently under development.

Specifically, the intermediate target is the demonstration of $35/dry ton cellulosic biomass feedstock for all major feedstock types at the pilot scale by 2012. A more detailed explanation of feedstock types is provided in section D.2.

D.1 The 2012 Feedstock Cost Target

The feedstock R&D path is based on the 2012 feedstock cost target of $35/dry ton. This target includes all aspects of feedstock supply up to the point of insertion into the conversion process (see Figure D-1). As such, the biomass feedstock cost includes purchase (the grower payment in the case of crop residues and energy crops or the stumpage cost in the case of forest residues), harvest and collection, storage, pre-processing, transportation, and additional handling, queuing, and other operations. Also included is the interface between supply and conversion (i.e., feedstock optimization for conversion and delivery to the "throat of the reactor"). This interface definition holds regardless of the conversion technology or feedstock type. From a cost perspective, the $35 can be divided into:

- Feedstock value – $10 for 130 million dry tons (or about 10% of the 1.3 billion)
- Farm gate price – variable based on the supply system scenario
- Biorefinery plant gate price – variable based on the supply system scenario

- Feedstock cost to the starting point of the conversion process (or “throat of the reactor”) – \$35/dry ton (which includes the \$10 feedstock value and is based on 2002 U.S. dollars).

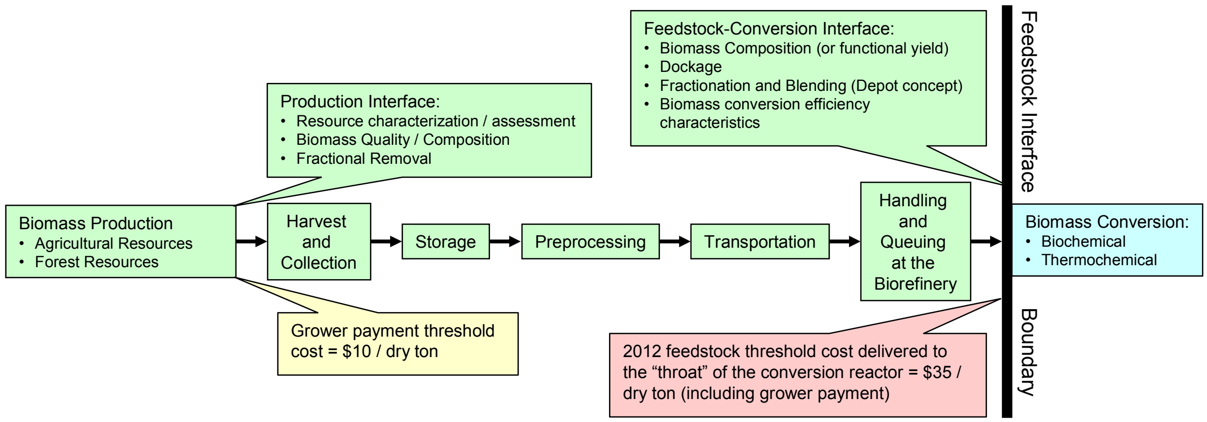


Figure D-1. The 2012 Feedstock Supply Scope (green boxes) and Cost Target (red box)

Feedstock value is the price that must be paid for biomass, on the land, to purchase it from the producer (e.g., a farmer or forester). Different feedstocks have different median and average values (Perlack et al. 2005), and their price ranges vary from less than \$10/dry ton to \$40/dry ton and more in some cases (Perlack and Hess 2006). The reasons for this variability are as diverse as the geographic regions and growers that produce biomass. However, the single largest variable is tied to the tonnage demanded and competing demands such as soil/agronomic sustainability.

Using POLYSYS (De La Torre Ugarte and Ray 2000), it was estimated that 10% of the potential 1.3 billion ton domestic biomass resource could be purchased at or less than \$10/dry ton (see also Section 4.1.1). The analysis demonstrated that this 10% resource availability was not uniform on a per-acre basis or across resource type; rather, the 10% resource availability comes from the sum of all acres and biomass resources. This analysis is important to the 2012 feedstock R&D and cost targets for two reasons. First, based on the market demand estimates for cellulosic ethanol, the cellulosic biomass resource demand will not exceed 130 million dry tons until sometime after 2015 (Chapter 2). Thus, the \$10/dry ton feedstock threshold value for an estimated 130 million dry tons is a practical feedstock cost estimate for the 2012 cost target. Second, the 130-million-dry-ton estimate includes all major feedstock types, so feedstock supply system technologies must be developed and validated for each of the major feedstock types.

The farm gate and processing plant gate feedstock pricing structures are commonplace in agriculture supply systems, but they can be dynamic and variable based on the farm-agribusiness relationship. In the integrated feedstock assembly scenario, farmers are responsible for harvesting, collection, and delivery to storage. These assembly functions are integral to production and, thus, remain under the producer’s control (even if he chooses to have them performed by others). Often, farm gate pricing is based on feedstock value plus these on-farm operations. The agribusiness is then responsible for feedstock procurement and storage, pre-processing, transportation, and handling. However, if the biorefinery uses a distributed on-farm storage system (or some other on-farm value process), the agribusiness may arrange for the farmer to store the material, which will change farm gate pricing. The agribusiness may also choose to subcontract feedstock assembly operations before the biomass reaches the biorefinery gate, which also would alter plant gate pricing.

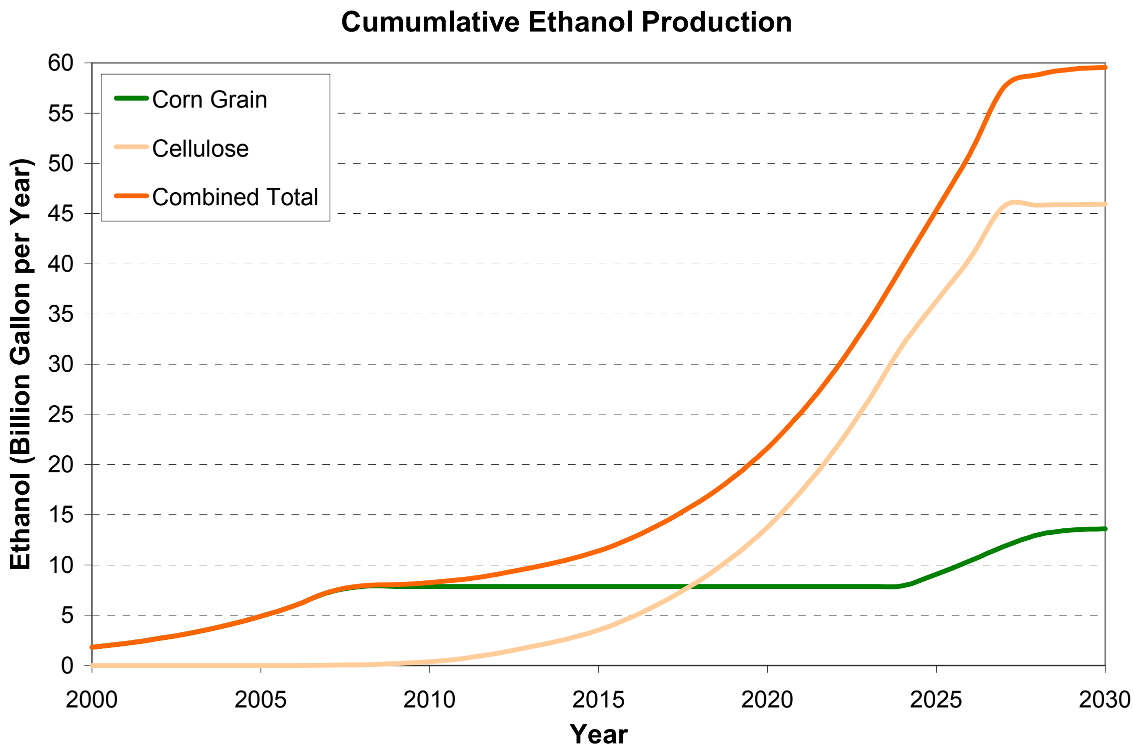


Figure D-2. Projections for Growth of Ethanol Production

Each of the business elements of the feedstock supply chain must work seamlessly with the others to provide biomass to the biorefinery. However, the seamless integration of business elements does not mean the entire biomass production, supply, and conversion system must employ common technologies and decision criteria. In fact it likely will not, which makes farm gate and plant gate pricing variable across feedstocks and regions. As such, it is important that the feedstock R&D plan consider technologies and costs in terms of farm gate and biorefinery plant gate interfaces. However, the variable costs and technology characteristics of these interface points do not make good cost targets.

Because farm gate and plant gate costs do not represent feedstock supply system end-state costs, the biomass feedstock cost of $35/dry ton delivered to the "throat of the reactor" has been established as the feedstock R&D 2012 interim cost target. This is the feedstock cost assumption for the interim ethanol cost target of $1.07/gallon ethanol by 2012. By setting the biomass feedstock cost target at the entry point of the conversion process, all feedstock supply system unit operations are included in the feedstock R&D scope. This also allows R&D technology development to be optimized across all feedstock supply business elements and unit operations.

D.2 Feedstock R&D Pathways to Achieve the 2012 $35/Dry Ton Cost Target

The goal of feedstock R&D is to create technology that provides a feedstock supply of 10% of the 1.3 billion dry ton feedstock potential (about 130 million dry tons) accessible at $35/dry ton. To be successful, near-term R&D should:

- Specifically target the remaining production, harvest and collection, pre-processing, storage, and transportation barriers for dry, wet, and woody feedstock supply systems
- Employ a range of participants to capture expertise in diverse areas
- Maximize interfaces between participants and other program elements
- Include pilot-scale demonstration to optimize process integration and identify scale-up issues.

The key activities and milestones are shown in Figure D-3.

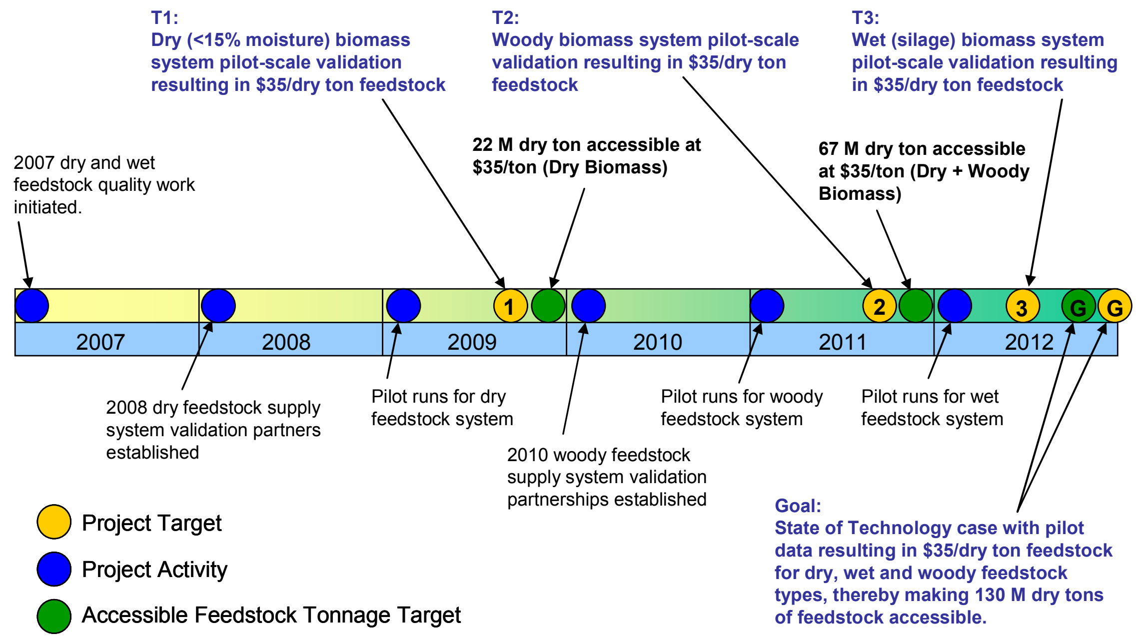


Figure D-3. Timeline of Near-term Feedstock Cost and Tonnage Goals

D.2.1 The Feedstock Supply System

Figure D-4 is a general process diagram of the feedstock supply system. It also includes barriers to the feedstock cost target. The barriers represent feedstock supply system performance metrics that underpin feedstock cost and supply. The performance metrics include:

- Efficiency – The operational costs—as influenced by materials, supplies, labor, logistical issues, and material losses—associated with particular equipment configurations
- Capacity – The throughput of particular equipment or sets of equipment

- Quality – The product specifications, value, and functional end-product yields of the biomass passing through the supply system. Quality is intrinsically linked to capacity and efficiency.

These metrics relate to the delivered feedstock cost according to the following equation:

$$\underset{(\$/\text{ton})}{\text{Feedstock Cost}} = \left(\underset{(\$/\text{ton})}{\text{Grower Payment}} \right) + \left(\frac{\text{Efficiency } [\$/\text{hr}]}{\text{Capacity } [\text{ton/hr}]} \right) + \text{Quality } [\$/\text{ton}]$$

Since these metrics encompass the supply system factors that affect feedstock cost, all feedstock R&D activities focus on one or more of these metrics in order to reduce feedstock cost and achieve the $35 cost goal.

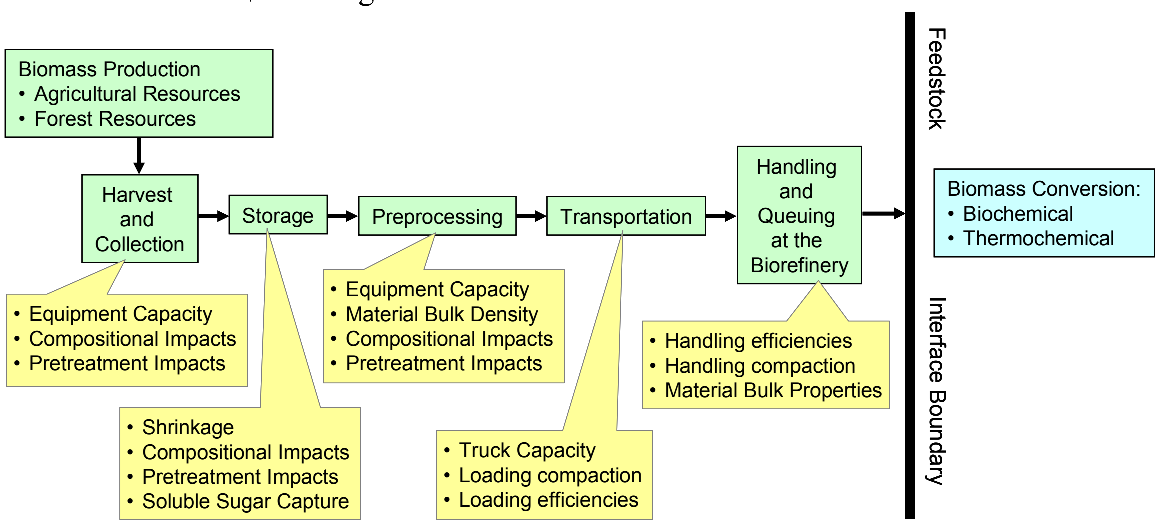


Figure D-4. Feedstock Supply Schematic for $35/dry-ton Feedstock

The performance metrics are distributed across the elements of the feedstock supply system. These elements encompass all the unit operations necessary to move biomass feedstocks from the land resource to the conversion process of the biorefinery (Cushman et al. 2003).

- Biomass production is the beginning of the feedstock supply chain. It involves producing feedstocks to the point of harvest. Production includes the determination of factors such as feedstock type, land use, policy, and agronomic practices that drive biomass yield and directly affect harvest and collection operations.
- Harvest and collection encompasses all operations associated with getting the biomass from its source to the storage or queuing location. In addition to obvious operations such as cutting (or combining, swathing, or logging) and hauling, harvest and collection often includes some form of densification (such as baling, bundling, or chipping) to facilitate handling and storage.
- Storage and queuing are essential operations in the feedstock supply system. They are used to deal with seasonal harvests and variable yields and delivery schedules. The objective of a storage system is to provide the lowest-cost means of holding biomass

material in a stable, unaltered form (i.e., neither quality improvements nor reductions) until it is called for by the biorefinery.

- Pre-processing occurs prior to the conversion process to physically transform feedstock into the format required by the biorefinery. Pre-processing can be as simple as grinding and formatting biomass for increased bulk density and improved conversion efficiency or as complex as improving feedstock quality through fractionation, tissue separation, and blending.
- Transportation generally consists of moving biomass from a storage location to a biorefinery via truck, rail, barge, or pipeline. The system used directly affects how the feedstock is handled and fed into the conversion process. Because the transportation and handling of feedstock are dependent on the format and bulk density of the material, these operations are tightly coupled to each other and all other operations in the feedstock supply chain.

D.2.2 Feedstock Classifications, Targets, and Performance Metrics

Achieving the 2012 objective requires that multiple supply systems, representative of the major feedstock types, be developed. These types, categorized according to feedstock resource, are:

- Dry herbaceous (model pathway – straw and stover primarily from irrigated lands)
- Wet herbaceous (model pathway – stover and switchgrass primarily from rain fed lands)
- Woody (model pathway – logging residues)
- Energy Crops (model pathway – switchgrass).

This categorization is defined by the major technology and capital equipment changes required for each feedstock type. For example, regardless of the crop, all herbaceous biomass with less than 15% moisture is handled and managed with similar technologies and processes. Differences among these crops tend to be compensated for through equipment tuning and management. However, those same biomass crops in a high-moisture (more than 50% moisture) system require different technologies and capital equipment. The same is true for woody biomass. Energy crops, which can be herbaceous or woody, justify a separate feedstock classification because of production and crop development and introduction considerations. However, supply logistics and conversion issues for energy crops are similar to those of herbaceous (wet and dry) and woody crops.

D.2.2.1 Dry Herbaceous Supply System

Dry herbaceous feedstocks (e.g., corn stover, cereal straws, milo stover, and switchgrass) consist of crop residues and herbaceous energy crops with moisture contents less than 15%. Because the moisture content limit is dictated mainly by storage requirements, biomass that is more than 15% moisture at the time of harvest may be dried prior to storage and included in the dry herbaceous classification. An analysis of biomass resources in the “Billion Ton” study showed the net potential supply of dry crop residue feedstocks to be about 22 million dry tons by 2012 (Perlack et al. 2005).

The primary challenge of the feedstock assembly core R&D in the dry herbaceous feedstock supply system is migrating from traditional technologies, which primarily serve the smaller distributed livestock and forage industries, to an assembly system specifically designed for the biorefinery industry. This new design considers policy, logistics, and agricultural practices that affect feedstock supply; alternatives to the delivery of bales to the biorefinery; pre-processing as an integrated component of feedstock assembly; and feedstock quality impacts on the biorefinery conversion processes.

Dry herbaceous feedstocks have been the model feedstocks of the feedstock platform. As shown by the 2006 state-of-technology assessment in Figure D-5, the dry herbaceous feedstock supply system is well-developed, and significant progress has been made toward achieving the $35/dry-ton cost target. A significant aspect of dry feedstocks core R&D has been the transition from a bale to a bulk feedstock system. Thus, the challenge for dry feedstock core R&D is not to find new, undeveloped technologies but to pursue improvements to the bulk technology already under study. The R&D activities required to accomplish these technology advancements and to achieve the cost improvements shown in Figure D-5, are shown in Table D-1.

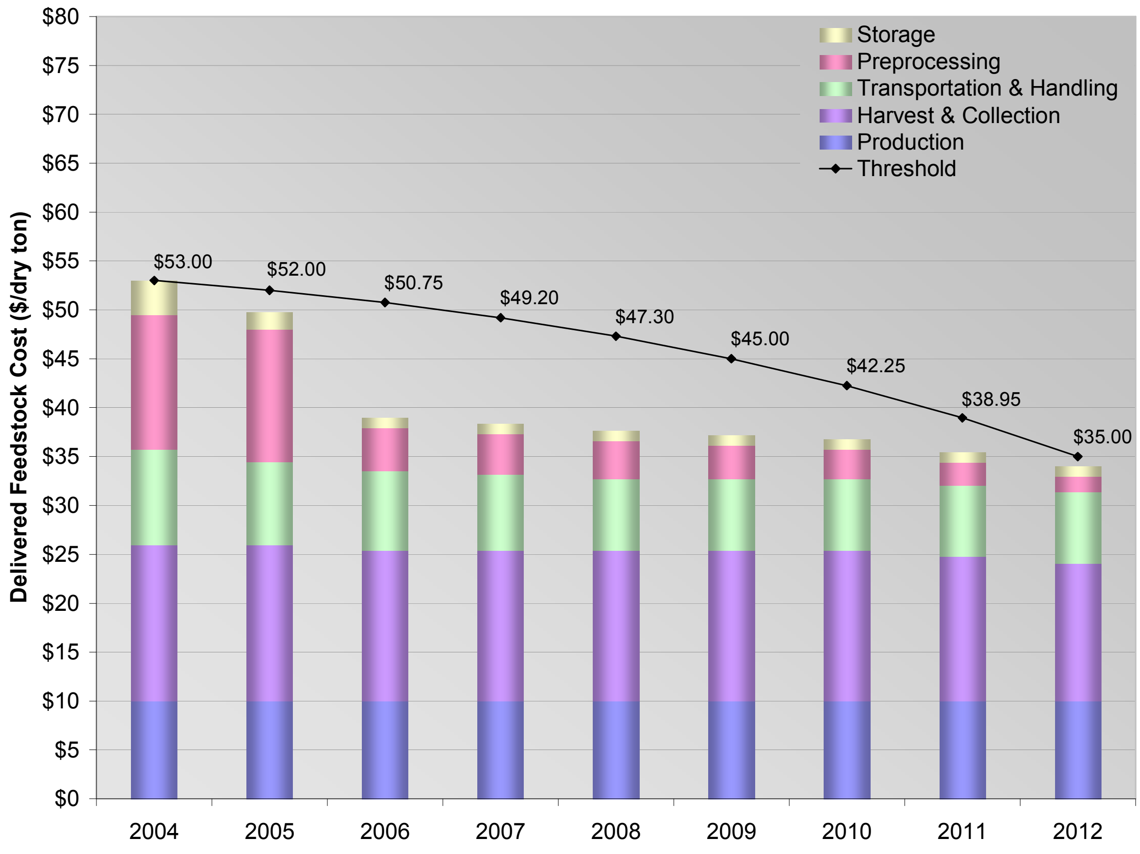


Figure D-5. Dry Feedstock Assembly Threshold Cost Curve and Associated Unit Operation Cost Reductions

Feedstock cost and quality are dependent on the targets and performance metrics associated with the R&D activities identified in Table D-1 as well as market and policy drivers. The sensitivity and risk associated with market and policy drivers are handled at the industry scale with appropriate models. However, the implied risks associated with feedstock assembly core R&D and analyses are assessed by applying a single-value uncertainty interval analysis to key feedstock technical parameters. This analysis requires a model that can quantitatively determine the costs of feedstock assembly operations. The model is then used to evaluate the high, mid, and low range of each technical parameter and provide the relative sensitivity of each parameter within the feedstock assembly system. The dry feedstock assembly system is the most mature in terms of engineering data and assembly system models that specifically incorporate the R&D needs of the conversion processes. These data and models were used to determine the range of sensitivity of each of the dry feedstock technical parameters as well as the relative costs associated with unit operations and other cross-cutting costs.

Table D-1. Timeline of Key Feedstock R&D Activities for the Dry Feedstock Supply System

	DRY	Completion Year							
	R&D Area	2006	2007	2008	2009		2010	2011	2012
Interface	Feedstock Conversion Interface	Establish value and quality requirements for dry preprocessed and stored biomass for delivery to a biorefinery		Verify pretreatment and conversion techno-economic values associated with fractions produced within core R&D unit operations (i.e., define dockage values)		2009 Validation of the Dry Feedstock Supply System for 22 Mtons at $35/dry ton			
Feedstock Infrastructure Core R&D	Sustainable Harvest & Collection	Quantify selective harvest value by identifying quality impacts (both compositional and functional) on the conversion process							
Feedstock Infrastructure Core R&D	Preprocessing	Increase grinder efficiencies and resulting material bulk densities by coupling the understanding of biomass deconstruction and biomass rheological properties	Build, instrument, and test size selective grinder configurations to optimize machine capacity and material bulk density to meet established performance targets	Build, instrument, and test optimum grinder configuration based on FY07 results that include a multi-feed input system, dust control, safety features, etc., to meet FY09 validation tests	Validate preprocessing performance targets based on established analysis designs.				
Feedstock Infrastructure Core R&D	Storage & Queuing	Quantify storage options and mitigation strategies to minimize dry matter losses (<5%) and maximize potential compositional and functional biomass improvements	Evaluate dry biomass storage configurations and protection strategies for high moisture environments		Validate storage and queuing system performance targets based on established analysis designs				
Feedstock Infrastructure Core R&D	Transportation & Handling		Build, instrument, and test High throughput biomass compaction systems (i.e., tapered auger) to meet established transport, load-out, and handling performance targets	Build, instrument, and test optimum compression configuration based on FY07 results to meet FY09 validation tests	Validate storage and queuing system performance targets based on established analysis designs				
Analysis	Integration/ Modeling Analysis	Completion of integrated supply system model in support of draft $35/dt analytical engineering design	Employ integrated supply system model to evaluate unit operation designs for multiple regions		Completion of integrated supply system model in support of $35/dt validation per unit operation specifications				

The tornado chart shown in Figure D-6 presents the range of sensitivity for each of these parameters. The ranges are based on the 2012 delivered feedstock target of $35/dry ton and illustrate the potential of each parameter to affect overall assembly system cost through engineering and quality. The chart is split into three regions: (1) specific research technical parameters that directly affect the cost and quality of delivered feedstocks, (2) unit operations that make up the assembly system, and (3) variable costs that cross-cut assembly system operations. The research technical parameters are the primary focus of the risk analysis because their effects determine if and how the cost targets are met. The other two regions show the relative effects the technical parameters have on the assembly system as a whole. The ranking of each parameter implies some degree of R&D risk. Those parameters with large cost ranges have greater potential to affect the 2012 targets (positively or negatively). However, inherent in the single-value analysis approach is the inability to identify the interdependence of parameters. Although a Monte Carlo analysis could determine this interdependency, the feedstock assembly system models are too immature to provide the input ranges required.

Thus, Figure D-6 assists in identifying and directing R&D based on relative potential but cannot be used to determine the effect of changing a single parameter on related parameters. Nevertheless, it is expected, based on the nature of each feedstock assembly unit operation, that synergistic credits or debits will be realized. This suggests that an integrated R&D approach is necessary.

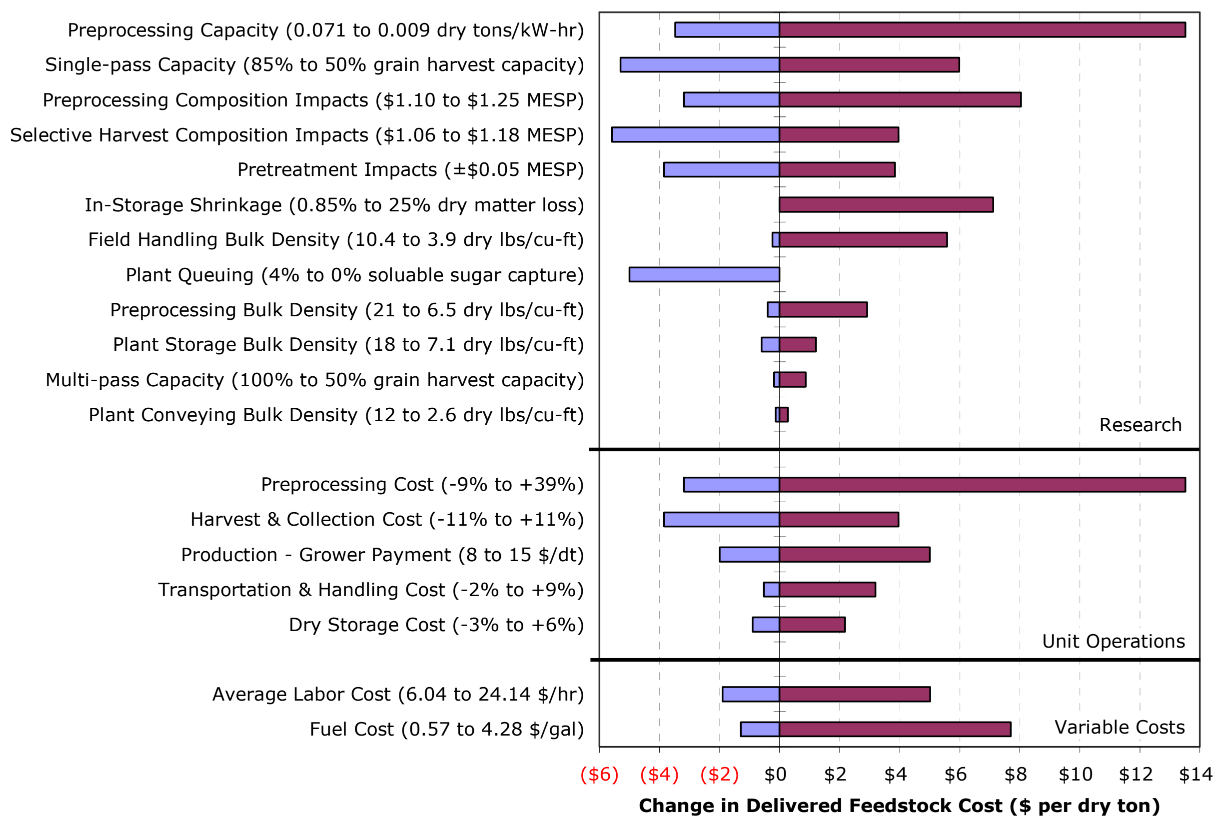


Figure D-6. Sensitivity Analysis of Technical and Logistical Parameters in the Dry Feedstock Assembly $35/dry-ton Case

D.2.2.2 Wet Herbaceous Supply System

Wet herbaceous feedstocks (e.g., corn stover, milo stover, and switchgrass) consist of crop residues and herbaceous energy crops that primarily require anaerobic storage and have enough moisture at the time of storage to support anaerobic stability. These feedstocks would degrade if a dry storage technique were applied. Wet feedstocks are the result of:

- Harvesting in wet conditions because of agronomic and environmental factors
- Assembly and storage in locations with high humidity or rainfall throughout the year
- Large supplies of wet biomass (e.g., bagasse) made available as a byproduct of another process.

An analysis of biomass resources in the "Billion Ton" study (Perlack et al. 2005) showed the net potential supply of wet herbaceous feedstocks to be about 38 million dry tons by 2012. However, the use of wet herbaceous feedstocks is currently limited by a host of infrastructure barriers. As a result, wet feedstock costs are well beyond the $35/dry-ton cost target, Figure D-7. Because wet herbaceous feedstocks represent a significant portion of the overall feedstock resource, overcoming these barriers provides the greatest potential for achieving the tonnage targets.

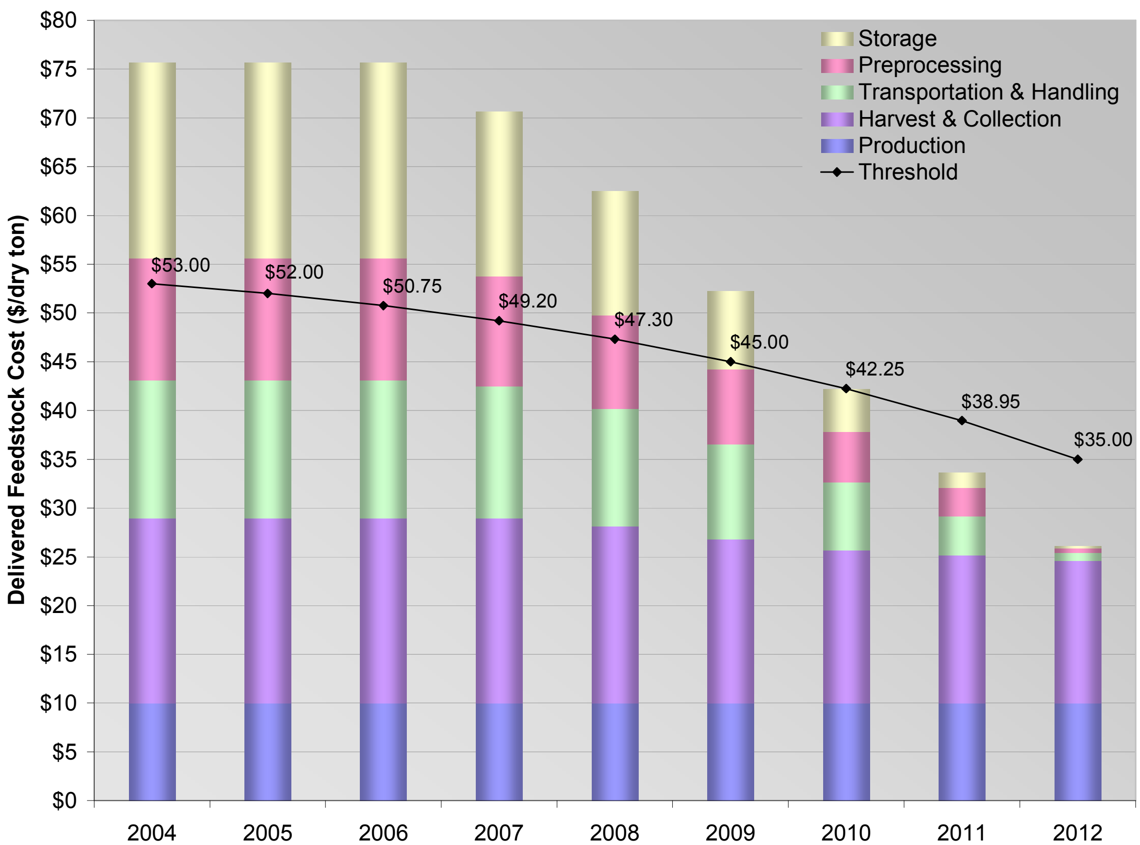


Figure D-7. Wet Feedstock Assembly Threshold Cost Curve and Associated Unit Operation Cost Reductions

Once again, one of the challenges of feedstock assembly core R&D in the wet herbaceous feedstock supply system is migrating from traditional technologies to an assembly system specifically designed for the biorefinery industry. An additional challenge is the development of value-added operations that improve feedstock quality for the biorefinery. Without value-added operations to offset high feedstock costs, a large percentage of feedstock resources will not be available at the $35/dry-ton cost target. These value-added operations—which include quality (composition and pretreatment) enhancements and soluble sugar capture in storage—combined with equipment capacity and efficiency improvements form the basis of the R&D activities for the wet herbaceous supply system. This R&D plan is shown in Table D-2.

Based on the R&D activities shown in Table D-2, specific targets have been identified for key technical parameters of the wet herbaceous supply system. Figure D-8 shows the sensitivity of these R&D parameters specific to a wet feedstock assembly system. Each parameter is based on the 2012 delivered feedstock target of $35/dry ton. The figure illustrates the relative effect of each parameter on assembly system cost and feedstock quality. Unique to wet feedstock is its potential to use value-added technologies to affect feedstock cost and quality. Specifically, the free sugar capture and reduced pretreatment severity parameters have the potential to offset storage, pre-processing, and transportation costs, which are higher than the respective dry system costs because of the water content of the feedstock.

Table D-2. Timeline of Key Feedstock R&D Activities for the Wet Feedstock Supply System

	DRY	Completion Year							
	R&D Area	2006	2007	2008	2009		2010	2011	2012
Interface	Feedstock Conversion Interface	Establish value and quality requirements for dry preprocessed and stored biomass for delivery to a biorefinery		Verify pretreatment and conversion techno-economic values associated with fractions produced within core R&D unit operations (i.e., define dockage values)					
Feedstock Infrastructure Core R&D	Sustainable Harvest & Collection	Quantify selective harvest value by identifying quality impacts (both compositional and functional) on the conversion process				2009 Validation of the Dry Feedstock Supply System for 22 Mtons at $35/dry ton			
Feedstock Infrastructure Core R&D	Preprocessing	Increase grinder efficiencies and resulting material bulk densities by coupling the understanding of biomass deconstruction and biomass rheological properties	Build, instrument, and test size selective grinder configurations to optimize machine capacity and material bulk density to meet established performance targets	Build, instrument, and test optimum grinder configuration based on FY07 results that include a multi-feed input system, dust control, safety features, etc., to meet FY09 validation tests	Validate preprocessing performance targets based on established analysis designs.				
Feedstock Infrastructure Core R&D	Storage & Queuing	Quantify storage options and mitigation strategies to minimize dry matter losses (<5%) and maximize potential compositional and functional biomass improvements	Evaluate dry biomass storage configurations and protection strategies for high moisture environments		Validate storage and queuing system performance targets based on established analysis designs				
Feedstock Infrastructure Core R&D	Transportation & Handling		Build, instrument, and test High throughput biomass compaction systems (i.e., tapered auger) to meet established transport, load-out, and handling performance targets	Build, instrument, and test optimum compression configuration based on FY07 results to meet FY09 validation tests	Validate storage and queuing system performance targets based on established analysis designs				
Analysis	Integration/ Modeling Analysis	Completion of integrated supply system model in support of draft $35/dt analytical engineering design	Employ integrated supply system model to evaluate unit operation designs for multiple regions		Completion of integrated supply system model in support of $35/dt validation per unit operation specifications				

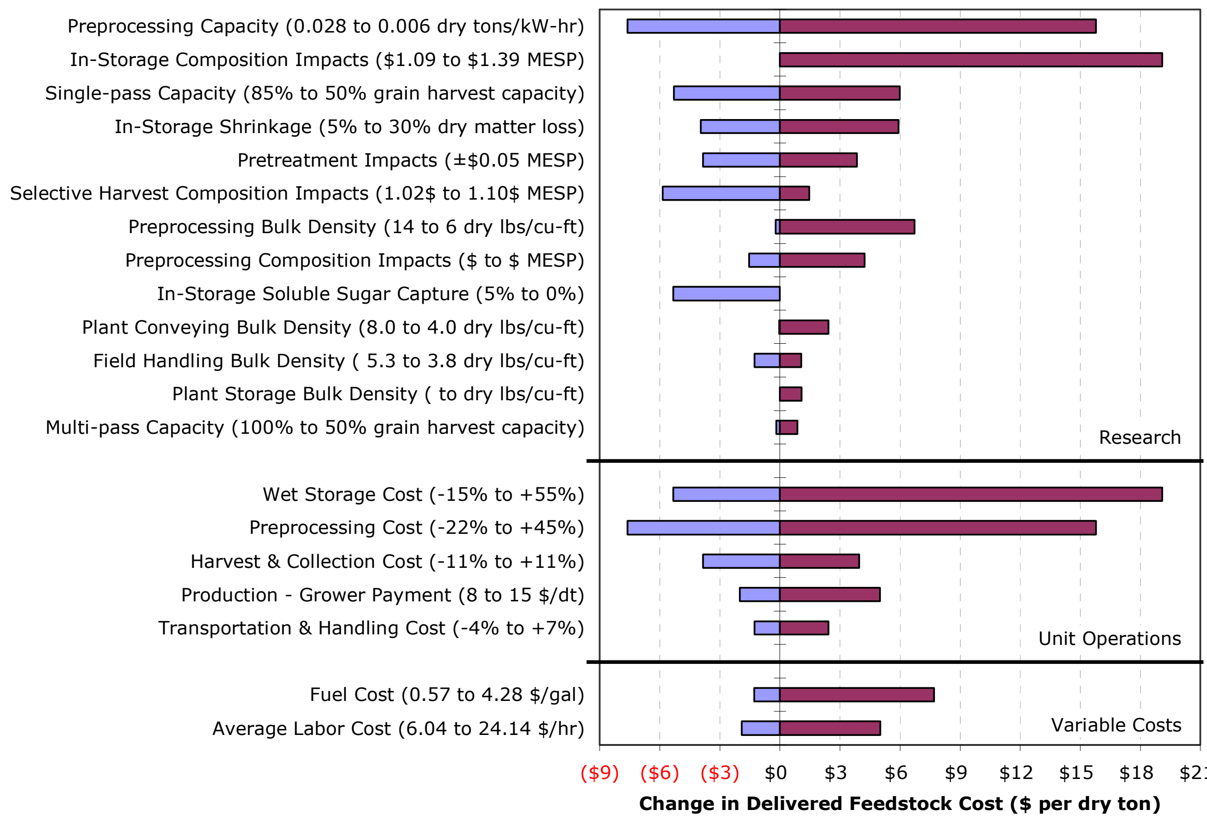


Figure D-8. Sensitivity Analysis of Technical and Logistical Parameters in the Wet Feedstock Assembly $35/dry ton Case

D.2.2.3 Woody Supply System

The "Billion Ton" study estimated that 225 million dry tons of forest residues are potentially available for bioenergy. This excludes the 35 million dry tons of fuel wood used for residential and commercial space heating, 8 million dry tons of urban wood wastes used to generate power, and nearly 100 million dry tons of forest biomass residues used by the forest products industry. Also excluded are perennial woody crops grown on crop land, as opposed to forest land (Perlack et al. 2005). Forest residues come from the following sources:

- Primary
  - Logging residues from conventional harvest operations and residues from forest management and land-clearing operations
  - Forest thinnings from wildfire prevention projects (fuel treatments)
  - Fuel wood extracted from forest lands
- Secondary
  - Wood residues from forest products industry mills that process primary wood products

- Pulping liquors (black liquor)
- Wood residues from secondary processing mills

- Tertiary
  - Urban wood residues (e.g., construction and demolition debris, tree trimmings, packaging wastes, and consumer durables).

Logging residues and forest thinnings will account for the major portion of forest residues for ethanol production (see Figure D-9). The near-term woody feedstock available consists largely of logging residues, based on the expectation that some aspects of harvesting costs are predominantly deferred to the primary logging operations producing the residues. That is, the recovery of logging residue is presumed to be carried out concurrently with the harvesting of conventional forest products. The available logging residue resource is estimated at about 41 million dry tons by 2012, taking into account recovery and equipment limitations. Additional resources may be collected if more efficient and cost-effective equipment designed specifically for residue collection becomes available.

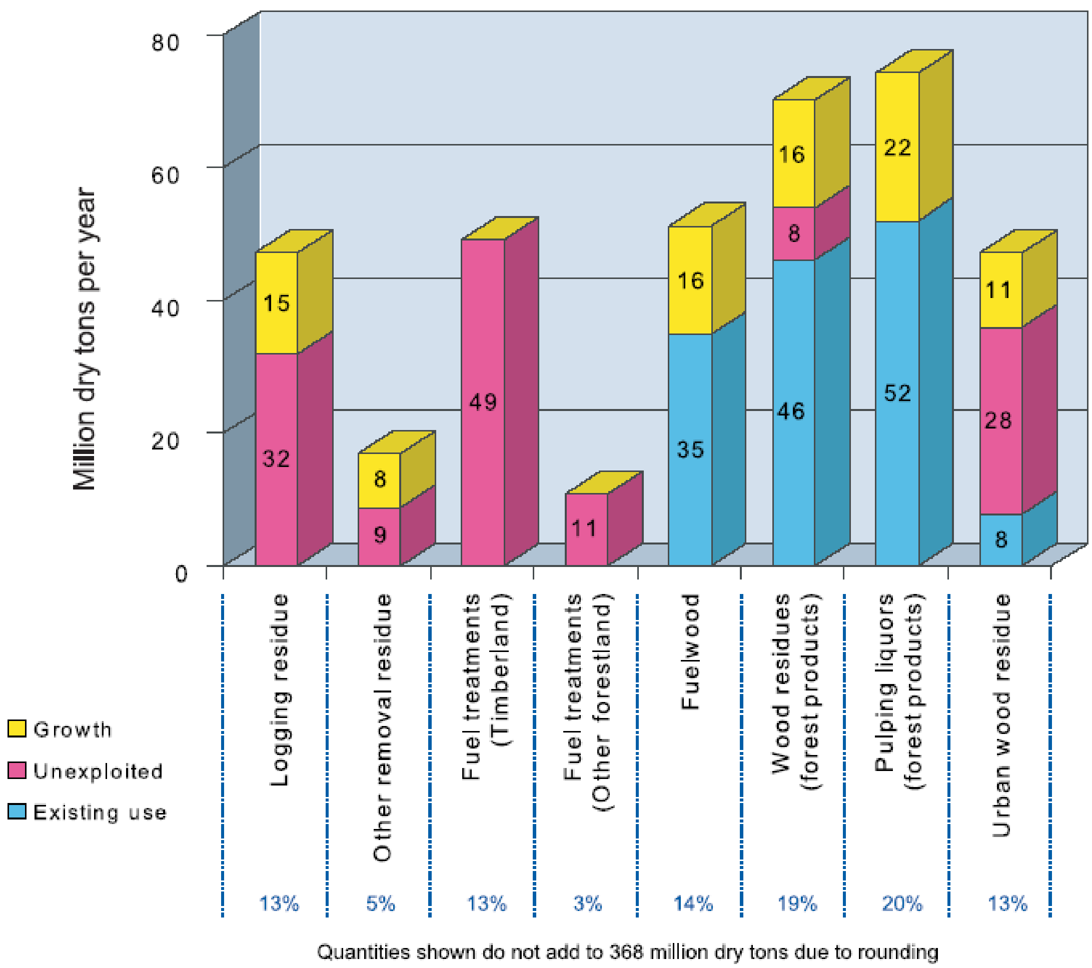


Figure D-9. Potential Woody Biomass Resources

The annual recoverable forest residue resource from thinning operations for wildfire prevention is estimated to be at least 50% more than the logging residue resource. However, forest thinnings—especially those associated with the reduction of fire hazards—are not considered available in significant quantities within the 2005–2012 period. This is primarily because of the need for more concrete implementation policies for the Healthy Forest Restoration Act of 2003 and the need for technologies that would allow cost-effective recovery.
The three key areas to the achievement of the $35/dry-ton cost target and the feedstock supply targets for woody feedstocks are:

- **Cost and efficiency**
  The current supply system for markets of woody biomass (e.g., timber, pulp and paper, fuel wood, and urban residues) varies with respect to equipment, products, land use, markets, and revenues. In addition, the resource environment varies with respect to policy, accessibility, slope, and compaction. It is therefore clear that the cost and efficiencies of woody supply systems will vary significantly. However, the woody supply system has two advantages: (1) The markets for woody resources and the infrastructure to support those markets are well established, and (2) it is possible to store the biomass "on the stump." One remaining challenge is the equipment used in the wood products supply systems. It may not be the best equipment for a wood residue supply system. Thus, assessing the cost and efficiency of the woody feedstock supply system is a critical component of this research.
- **Supply security and accessibility**
  The factors that affect woody feedstock supply are much different than those that affect herbaceous feedstocks. The supply and availability of crop residues and energy crops are determined by the risk, profit, and agronomic/environmental decisions of individual growers. The supply of woody residues is affected by a multitude of factors such as land use policies and economics, crop maturity rates, and sustainability and water quality factors. Consequently, analysis of supply security and accessibility of woody feedstocks is a critical component of this research.
- **The feedstock conversion interface**
  The feedstock conversion interface is the basis for feedstock quality upgrade components. This interface expanded the feedstock key research areas from cost and efficiency elements to include quality elements critical to achieving the cost and tonnage targets of 2012 and beyond. The potential for quality upgrades through biomass fractionation and other innovative pre-processing options is assumed to exist. Therefore, developing, validating, and exploiting (through engineered systems) feedstock quality impacts is a critical component of woody feedstock research.

Although these are overarching R&D issues of the woody supply system, a woody supply system state of technology (SOT) must be conducted to identify specific R&D targets and performance metrics for this feedstock type. This SOT, as well as other important R&D activities is included in the woody feedstock R&D plan shown in Table D-3.

Table D-3. Timeline of Key Feedstock R&D Activities for the Woody Feedstock Supply System

	Woody R&D Area	Completion Year 2006	2007	2008	2009	2010	2011	2012
Interfac	Feedstock Conversion Interface				Verify pretreatment and conversion techno-economic values associated with woody biomass fractions			
Feedstock Infrastructure Core R&D	Sustainable Harvest & Collection			Baseline harvest and collection systems costs and assess quality upgrade potential to identify infrastructure needs/modifications	Establish harvest and collection design configurations that meet cost and quality performance targets	Develop and test innovative equipment specific to the recovery of wood residues for each resource class and conditions where existing equipment is too costly and inefficient	Validate the achievement of established performance targets for harvest and collection systems	
Feedstock Infrastructure Core R&D	Preprocessing		Test the bulk densities, rheological properties and composition of standard formatted material produced by current woody biomass industries	Assess performance target improvements and potential equipment designs necessary to achieve the unit operation cost target	Establish preprocessing system design configurations that meet cost and quality performance targets	Test preprocessing system designs to determine hardware configurations capable of meeting established performance targets	Validate predetermined efficiency, capacity, and quality targets for a wet preprocessing system	
Feedstock Infrastructure Core R&D	Storage & Queuing			Baseline storage systems costs and assess quality upgrade potential to identify infrastructure needs/modifications		Build, instrument, and test prototype storage and queuing system configurations that meet established performance targets	Validate the achievement of established performance targets for storage and queuing systems	
Feedstock Infrastructure Core R&D	Transportation & Handling				Quantify the impact feedstock bulk densities and rheological properties have on the cost of transportation and handling systems and establish design configurations to meet performance targets	Establish transportation and handling design configurations that meet cost and quality performance targets	Validate the achievement of established performance targets for transportation and handling systems	
Analysis	Integration/ Modeling Analysis		State of Technology (SOT) assessment to establish unit operation performance targets		Completion of integrated supply system model in support of $35/dt analysis engineering design	Refine techno-economic model based on built and tested unit operation systems in support of $35/dt engineering design validation		

2011 Validation of the Woody Feedstock Supply System for 45 Mtons at $35/dry ton

D.2.2.4 Energy Crops Supply System

Energy crops include perennial grasses, forage-type crops, and trees grown specifically as feedstocks for bioenergy and bio-product facilities. Both herbaceous grasses and woody energy crops can grow on most of the approximately 400 million acres of land classified as crop land in the United States. These crops can also grow on land not suitable for conventional crops while providing the protection from erosion recommended for agricultural “set aside” or Conservation Reserve Program lands.

Switchgrass is a model herbaceous bioenergy crop. It is a high-yielding, native, perennial, warm-season grass that can be grown on a variety of sites. It is planted and harvested like a traditional hay crop and managed with existing agricultural equipment. Once established, it can produce for about 10 years before replanting is required. Switchgrass can be harvested dry using conventional baling equipment and delivered to biorefining facilities as large round or rectangular bales. The crop is also amenable to a wet feedstock supply system. Switchgrass was chosen as a model herbaceous bioenergy crop because it has relatively low energy and resource requirements, a high yield potential, and ecological value in the protection and improvement of soil quality and wildlife habitat. In addition, it is compatible with conventional farming equipment and management practices. Although many varieties of switchgrass are commercially available from forage seed companies, the best-producing varieties for energy crops may not be readily available because their production is not yet commercial. It may be necessary to establish a seed production stand within a project or contract 1–2 years in advance with seed production firms to obtain sufficient seed for large-scale plantings (see Figure D-10).

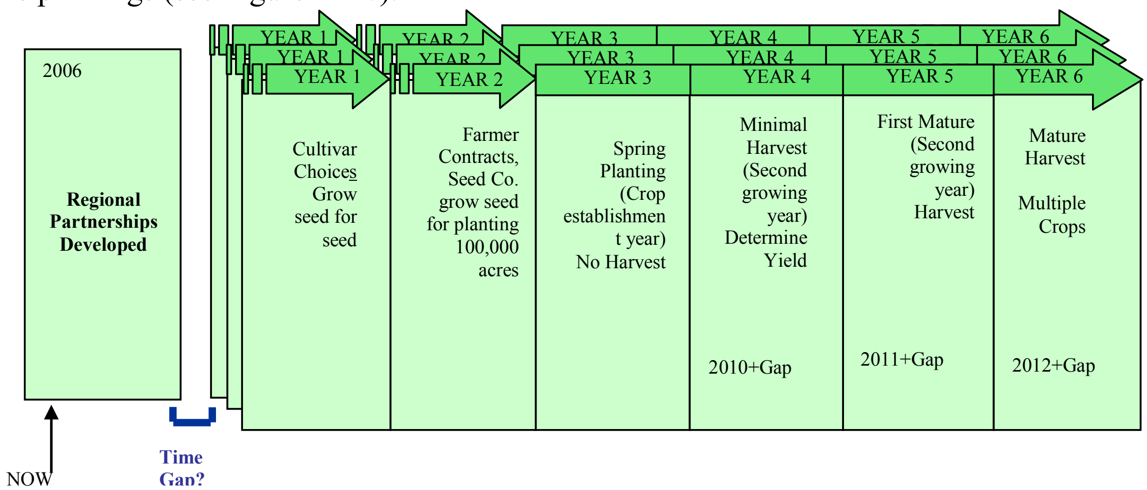


Figure D-10. Timeline for the Development of Herbaceous Energy Crops

Energy crops also include short-rotation woody crops such as hybrid poplar and hybrid willow. Hybrid poplar (or Populus spp.) is a widely distributed and genetically diverse species that can grow throughout the United States. It is established and managed with conventional agricultural equipment and harvested with existing forestry equipment (i.e., feller-bunchers, skidders, and whole-tree chippers). Willow (or Salix spp.) is also a widely distributed and diverse tree species. It, however, is recommended only for the Northeast and Lake States regions. Hybrid willow is planted at higher densities than poplar and harvested after 4 years of growth. Hybrid willow stands are regenerated by coppice or resprout. The planting and harvesting of willows require specially designed machinery that is commercially available in Europe. Both woody crops are usually delivered as whole-tree chips.

With the exception of production practices employed to grow perennial grasses, herbaceous energy crops can easily be accommodated by dry or wet feedstock supply systems. However, the woody energy crops, such as poplar and willow, are harvested in a manner similar to that of woody feedstocks. To the degree that energy crop feedstock systems mimic dry or wet systems, the sensitivity and risk associated with the dry and wet systems apply. Those energy crop systems that mimic the woody system require detailed data and models to assess the sensitivity of associated technical parameters.

D.3 The Comprehensive Feedstock R&D Pathway

The preceding sections introduced key issues and R&D activities associated with the development of supply systems for each of the feedstock types (i.e., dry, wet, woody and energy crops). While the scope and focus of feedstock R&D activities may differ for each feedstock type, the R&D pathways for the feedstock supply systems share the common elements and barriers illustrated in Figure D-4. Furthermore, the feedstock supply systems share performance metrics (i.e., efficiency, capacity, and feedstock quality). Therefore, to avoid the redundancy of presenting an R&D pathway for each of the feedstock supply systems, a single, comprehensive R&D pathway is presented here to represent, at a high level, the R&D activities needed to meet the intermediate feedstock cost and supply targets.

D.3.1 Production

Production is a critical component of the feedstock supply system, and it is a key research area for ensuring an adequate and sustainable feedstock supply. Through the USDA and regional partnership collaborations, validated assessments of feedstock resource type and potential will be accomplished. Specific research needed to address production issues will:

- Assess the cost and availability of the feedstock resource on a local basis to define production costs (e.g., grower payments) and identify regional tonnages available within each feedstock type or classification at or less than the feedstock threshold costs
- Identify and validate sustainable agronomic practices specific to feedstock types and regional variables to ensure sustainable production of the feedstock resource
- Investigate crop production improvements (e.g., increased yields, decreased yield variability, and consistent quality) through genetic modification
- Develop a perennial crop program that matches varieties to site conditions, establishes optimum agronomic practices, and creates a seed production capability.

D.3.2 Harvest and Collection

The feedstock R&D plan requires harvest and collection advancements in three key areas: (1) selective harvest (including forest-thinning operations), (2) single-pass or minimum impact harvest, and (3) harvest and collection efficiencies. The primary drivers for improved harvest system technologies are reduced costs and access to larger tonnages of biomass through increasing producer participation. For example, improved harvest technologies that address the soil quality issues of no-till farming (such as soil carbon sequestration, soil nutrient/water retention, erosion control, and soil compaction) will become increasingly important for enticing grower participation and accessing agricultural residues. Performance metrics for new harvest and collection systems include efficiency, equipment capacity, and quality. Without these improvements, the accessible biomass tonnage will remain restricted because of limited or niche producer participation. Specific research needed in this area will:

- Develop innovative harvest and collection methods for all resource types to eliminate or reduce unit operations and agronomic/operational impacts
- Quantify and validate harvesting-specific quality related to compositional impacts, pretreatment impacts, contaminant reductions, and bulk-handling improvements
- Develop and test innovative equipment specific to the recovery of wood residues for each resource class and conditions in which existing equipment is too costly and inefficient.

D.3.3 Pre-Processing

In the transition from a bale-based system to a bulk feedstock system, significant advances have been made in dry herbaceous pre-processing. However, additional advances are needed in three key areas: pre-processing equipment capacity, feedstock bulk density, and feedstock quality. Equipment capacity and bulk density directly affect feedstock cost and are important technical parameters to be addressed. Furthermore, a key component of feedstock R&D is to extend pre-processing beyond feedstock size reduction to include value-added operations that improve feedstock quality to the biorefinery. These operations involve fractionation and separation of higher-value feedstock components. Without value-added operations to offset high feedstock costs, a large percentage of feedstock resources will not be available at $35/dry ton. Specific research needed in this area will:

- Develop the pre-processing requirements for each feedstock type (This includes identifying the biorefinery feedstock requirements, pre-processing logistics, and storage, transportation, and handling requirements.
- Reveal the relationship between biomass structure and composition for the assessment of quality upgrade potential and the development of equipment and methods to achieve upgrades
- Establish an understanding of biomass tissue deconstruction in pre-processing and the relationships of the grinder configuration, tissue fractions, tissue moisture, and grinder capacity to optimize the grinder configuration for fractionation, capacity, and efficiency
- Increase bulk densities by coupling the understanding of biomass deconstruction and biomass rheological properties with innovative bulk compaction methods
- Control feedstock rheological properties resulting from pre-processing operations to provide a product that minimizes handling problems associated with transportation, handling, and queuing operations.

D.3.4 Storage

Feedstock shrinkage (or dry matter loss) is the main problem of feedstock storage, and shrinkage risks and mitigation strategies vary from region to region. DOE OBP's core R&D program has demonstrated that annual dry matter loss can be as low as 0.85%. But in wetter regions, dry matter loss may exceed 25%. To achieve the 2012 cost and supply targets, dry matter losses are targeted at less than 5% for all feedstock types. Specific research needed to achieve this will:

- Assess storage options and their effects on dry matter losses, compositional changes, and functional biomass changes (specific to resource type and regional variables)
- Establish baseline costs of storage systems at scales from 0.8 million tons/year to 10 million tons/year to identify key cost and infrastructure issues and develop paths to minimize industrial-scale storage costs
- Provide an understanding of soluble sugar and carbohydrate loss and evaluate the feasibility of preventing such losses or reclaiming soluble sugars and carbohydrates from feedstock during storage.

D.3.5 Transportation and Handling

Transportation operations can account for nearly 50% of the capital investment for a feedstock assembly system. Therefore, transportation costs can be a barrier to the use of feedstock resources. Because transportation operations do not add value to the feedstock, their costs must be reduced to the absolute amount feasible to achieve the $35/dry ton cost target. The feedstock R&D plan identifies feedstock bulk density as the key technical parameter that must be addressed to decrease transportation costs. As such, methods for increasing bulk density are a focus of feedstock R&D. In addition, because bulk handling is affected by feedstock rheological properties, this is an area of focus. Specific research needed to reduce transportation costs is:

- Provide an understanding of feedstock physical and rheological properties (including bulk density) as they relate to handling systems for optimizing handling and transportation efficiencies
- Provide an understanding of feedstock rheological properties in bulk storage to predict and minimize adverse feedstock physical changes that may affect plant processing
- Evaluate innovative transportation and handling methods.

D.3.6 Validation and Demonstration

As the dry, wet, and woody supply system technologies are improved and the milestones in Figure D-3 are achieved, the supply systems will be validated to demonstrate that resources can be supplied at the $35/dry-ton cost target. The validation will be performed in an integrated, pilot-scale facility that includes the supply system equipment and unit operations to demonstrate the capacities, bulk densities, rheological properties, composition, and quality that contribute to the $35/dry-ton feedstock cost for dry, wet, and woody feedstock systems.

D.3.7 Conclusions

An economically viable feedstock assembly system capable of delivering lignocellulosic biomass to a biorefinery for the production of ethanol must integrate many complex factors. These include five key unit operations (production, harvest and collection, storage, pre-processing, and transportation and handling), four feedstock types (dry, wet, woody, and energy crops), and various grower-specific agronomic and crop production practices as well as regional weather and topography constraints. The successful integration of these factors is dependent on technology advances made possible through core R&D activities and guided by core R&D and strategic analysis. Three fundamental R&D elements—efficiency, capacity, and feedstock quality—form the standard by which feedstock assembly technologies are quantified and implemented. These elements are inherently tied to one another such that changing one element for a specific part of the assembly system will affect the value of the other elements (positively or negatively). Thus, the purpose of the feedstock core R&D and analysis effort is to assess and advance the SOT of each unit operation within the assembly system specific to each of the four feedstock types and regional production constraints such that overall improvements in efficiency, capacity, and feedstock quality are realized.

Between now and 2012, feedstock assembly core R&D will addresses the barriers identified in the *Roadmap for Agricultural Biomass Feedstock Supply in the United States* (Cushman et al. 2003). Overcoming these barriers is necessary for the achievement of the intermediate target of demonstrating the delivery of $35/dry-ton cellulosic biomass feedstocks—including the four major feedstock types (dry, wet, woody, and energy crops)—at pilot scale by 2012.

D.4 Advanced Feedstock R&D Pathway to Achieve 2030 Tonnage Goals

By 2012, the biomass feedstock state of technology will include functional feedstock supply systems for all major types of biomass resources. That is, for agriculture resources, feedstock supply systems will be available for low-moisture (dry) crop residue, high-moisture (wet/silage) crop residue, and herbaceous energy crops. For woody resources, logging residue feedstock supply systems will be demonstrated and adapted to short-rotation woody energy crops and other high-potential forest resources (such fuel treatment thinnings). All of the feedstock supply systems will have demonstrated harvest, collection, storage/queuing, pre-processing, and transportation and handling at an integrated cost performance target of $35/dry ton. The biomass feedstock available at the $35 cost target is shown in Figure D-11, with the annual tonnages coinciding with the validation of the dry, woody and wet feedstock supply systems that will occur in 2009, 2011 and 2012, respectively.

Because every region of the United States has some biomass that could be accessed for a $10/dry-ton grower payment in 2012, feedstock supply technologies should not be a limiting factor for biorefinery development in any region or for any biomass resource. However, as the biorefining industry expands, economies of scale will drive biorefineries from 2,000-ton/day facilities to 5,000- and possibly 10,000-ton/day facilities. While such scaling favors conversion processes, larger scale biomass supply systems begin to incur greater costs. Increasing costs include, but are not limited to, those related to the transportation, handling, and integration of an expanded diversity of feedstocks that must be segregated or blended. Therefore, the longer-term feedstock supply R&D challenge is to develop technologies that control these costs so feedstock supply system costs will not limit achievable biorefinery scale efficiencies or consume biorefinery profits that could be used to purchase higher-value feedstocks.

An additional focus of the advanced feedstock platform R&D, is to ensure that the available biomass tonnages keep pace with the growth in ethanol demand (see Figure D-2 and Appendix J), with the ultimate goal of producing, supplying and converting in excess of 500 M dry tons of cellulosic biomass by 2030 (Figure D-11). For this to occur, the grower payment, which is influenced by production and sustainability issues, must increase substantially beyond the $10/ton level. In order to support the increased grower payment while maintaining profitability, additional advancements in supply system and conversion technologies must occur. The implementation of favorable policies (e.g., Farm Bill policies) may play a role as well.

With the focus on mitigating increasing supply system costs associated with larger scale biorefineries as well as on mitigating the increasing grower payment needed to insure adequate feedstock supplies, the advanced feedstock R&D goal will transfer from the 2012 $35/ton cost goal to the 2030 60M gallon ethanol production goal. The projected magnitude of the feedstock and conversion technology advancements needed to achieve the 2030 goal, measured in terms of allowable feedstock cost (i.e., the price the conversion process can pay for the feedstock without exceeding the 1.07/gallon production cost) is shown in Figure D-11.

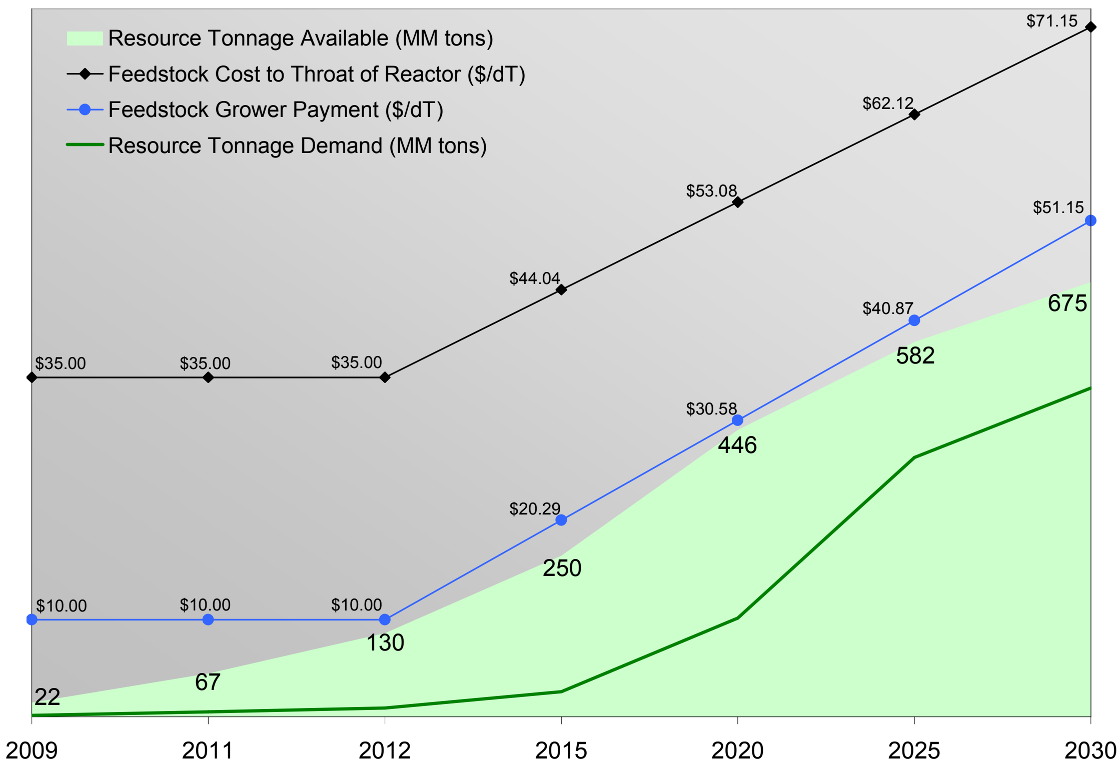


Figure D-11. Substantial Improvements in Supply System and Conversion Technologies will be Needed to Cover Increased Feedstock Costs without Exceeding Ethanol Cost Targets

New ideas have been proposed to control, and possibly reduce, feedstock supply system costs in large-tonnage systems by increasing the available biomass tonnage per square mile by increasing yields per acre and improving land use efficiency and productive capacity per square mile. These ideas include developing sustainable production systems that allow greater residue removal from existing crops and forest resources, putting more land into optimized sustainable production by integrating perennial energy crops with traditional crops and woody resources, and developing higher-yield crops and biomass cropping alternatives.

The immediate effect of increasing land area productivity is that a 5,000-ton/day biorefinery could operate on the same land-area footprint as a 2,000-ton/day biorefinery, thereby mitigating scale-up transportation issues. However, increased land-area productivity solutions are inherently multi-crop, and the feedstock supply system must be able to handle the diversity of those biomass resources. Fortunately, the United Sates grain handling and country grain elevator system provides a large-scale supply system model for a similar biomass "depot concept" to maximize the efficiency of delivering feedstock to large-scale biorefineries, Figure D-12.

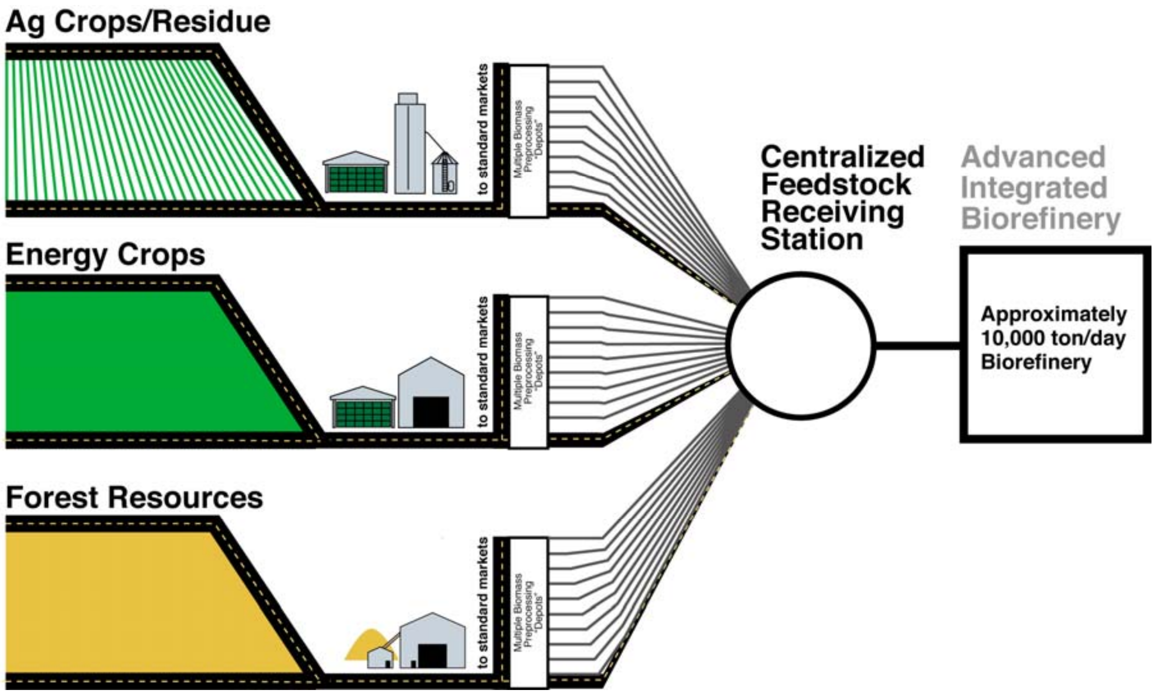


Figure D-12. Large-scale, Flexible Feedstock Supply System or "Depot Concept" to Handle and Merchandise a Diversity of Feedstocks across Large Geographical Areas

To develop a large-scale feedstock supply system that will enable conversion technologies to achieve optimum economic scales, feedstock supply long-term R&D will improve land use productivity/efficiency and advance feedstock supply technologies to handle larger volumes of biomass while controlling supply system costs. In addition, the production and removal of biomass on an annual basis can result in reduced crop yield. This presents a potential barrier to the use of biomass crop residues and energy crops as biorefinery feedstocks. Because these agricultural resources make up the largest biomass resource, this issue must be considered in large-scale biorefining. The factors that limit biomass removal will be addressed through partnerships with the USDA and biomass regional partnerships.

D.4.1 Increased Land Use Efficiency

Improved land use efficiency is dependent on the improvement of yields of existing crops and the development of new cropping alternatives. The joint DOE-USDA "Billion Ton" study (Perlack et al. 2005) assumed that historic trends of crop development and yield increase will continue. This assumption is dependent on the continued progress of the USDA, the land grant university system, and the agriculture industry through 2030, which is a reasonable assumption. Needed research for short-rotation woody crops includes the characterization of existing and potential woody crops in terms of yield, adaptation zones, and cost estimates for production and scale-up; the determination of practical aspects of scale-up such as establishment, cultural practices, and weed control strategies; and the development of genetics and targeted traits to accelerate species domestication. Needed research for perennial crops must address regional yields, genetic improvement, production management and costs, sustainability, and environmental production issues.

D.4.2 Advanced Large-Tonnage Feedstock Supply Systems

The advanced feedstock supply system must not only handle large tonnages of biomass over possibly larger geographical areas but also collect and assemble a multiplicity of feedstocks and convert those feedstocks into a “commodity spec” that can supply a common large-scale biorefinery. Primary research elements will include storage and queuing, pre-processing, and transportation and handling. The diversity of on-farm and in-forest systems must be accommodated not changed. The interface between producers and the commodity biomass system is a subtle but extremely important interface for large-scale feedstock supply technology development.

Additional research will include the development of depot-based feedstock pre-processing technologies to reformat and condition different feedstocks into a common, acceptable format and quality for improved transportation, handling, and conversion operations. Depot-based technologies will enable the feedstock assembly system to take advantage of advanced value-add operations such as fractionation and separation of biomass into secondary co-products for local markets (e.g., feed products). The co-products may be of higher value than the biorefinery feedstock and thereby will offset a larger percentage of supply system costs. In addition, depot-based technologies will enable feedstock blending to produce large-scale, commodity biomass at refinery-specified quality.

Advanced feedstock supply systems that handle large tonnages of biomass over wide geographical areas will rely heavily on the development of new transportation methods and technologies that incorporate value-added pre-processing and merchandising of raw feedstock material. Traditional biomass transportation modes, such as trucks, may not be economically possible because of transport distances, traffic congestion, and community opposition. Rail transport of biomass reduces the frequency of loads, but it is often more expensive than truck transport because of infrastructure constraints. Advanced transportation systems will likely incorporate technologies that not only provide infrastructure and operational cost savings but also incorporate in-transit value-added processes.

Appendix E: Biochemical Conversion Technology R&D Needs

Replacing 30% of U.S. 2004 finished motor gasoline demand (which equates to roughly 60 billion gallons) with ethanol by 2030 will require a significant increase in ethanol production over today's corn starch-based industry. Put simply, it will require the commercialization of cellulosic ethanol technology.

Currently, this is technically feasible for corn stover (Aden et al. 2003) and possibly poplar (Wooley et al. 1999) using biochemical conversion technology that includes pretreatment, enzymatic hydrolysis, and fermentation. However, the process remains inefficient and is therefore costly to commercialize. But ultimately, cellulosic ethanol production via biochemical conversion could provide fuel at prices commensurate with historical gasoline prices (i.e., less than $1/gallon) by taking advantage of breakthroughs in biotechnology.

Although this is the ultimate goal, it is useful to have an intermediate goal to provide ethanol that is competitive in the near-future transportation fuels market and that can be described and achieved with technology now under development. Taken together, these goals direct the path forward for biochemical conversion R&D. The intermediate target can be succinctly described as the demonstration of $1.07/gallon biomass-to-ethanol technology at pilot scale by 2012. The R&D needed to achieve this target is outlined here.

Achieving the intermediate target requires technology advancements in the key areas of pretreatment and enzymatic hydrolysis and sugar fermentation as well as the integration of these technologies. For the near-term R&D pathway to the $1.07/gallon target, an implicit assumption is that the lignin residue component of the process is burned to supply the heat and power needs of the plant using currently available technology. Detailed mass and energy balances validate this assumption (Aden et al. 2002). However, long-term, research is needed for better use of the lignin component to add value for enhanced fuel production. This is addressed in the context of advanced technology research (see Appendix G). In addition, the capital investment for cellulosic ethanol technologies is a significant hurdle. The research needs identified directly address this issue by reducing the total installed capital per annual gallon of output from the current 2005 state-of-technology estimate of $3.04/gallon to $1.85/gallon for the 2012 market target case.

The overall goal of biochemical conversion R&D is to create technology that provides market-competitive ($1.07/gallon), moderate-risk (evolutionary) technology tested at pilot-scale (1 ton/day) on a model feedstock (corn stover).

To be successful, near-term R&D should:

- Specifically target the remaining pretreatment, hydrolysis, fermentation, and integration barriers
- Employ multiple methods of overcoming a barrier (i.e., chemical and biological catalysis)

- Be based primarily on moderate risk or evolutionary development of the technology
- Include some revolutionary or novel technology development that complements the evolutionary emphasis
- Employ a range of participants to capture required expertise in diverse areas
- Maximize interfaces between participants and other program elements (e.g., feedstock development)
- Include 1 year of pilot production to optimize process integration and identify scale-up issues.

The key activities to achieve the target include:

- Meeting cost targets for delivered feedstock
- Developing pretreatment technologies that produce high xylose yields
- Developing new accessory enzymes to aid pretreatment efficacy
- Further reductions of cellulase cost via improvements in activity or other elements
- Developing a commercially viable, co-fermenting micro-organism capable of producing ethanol at high yields, rates, and titers in pretreatment hydrolyzates.

Figure E-1 depicts these critical activities on a timeline. Table E-1 provides more detailed information.

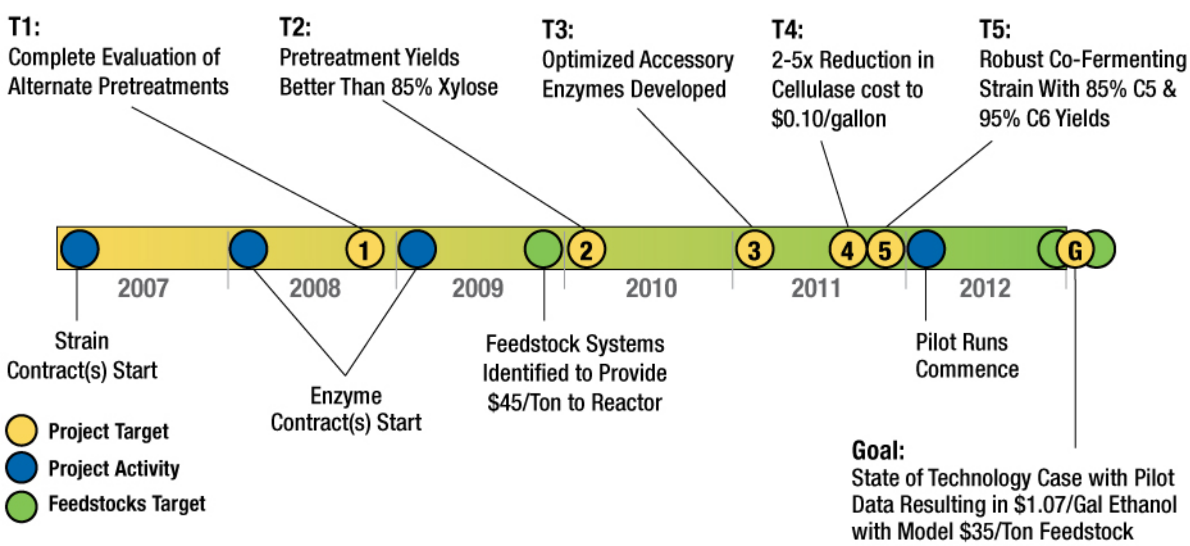


Figure E-1. Critical Targets and Activities for Pilot Demonstration of $1.07/gallon Technology

Table E-1. Timeline of Key Activities to 2012

	Completion Year						
R&D Area	Current	2007	2008	2009	2010	2011	2012
Feedstock Interface	Corn stover	Determine which feedstock types will be used in pioneer plants and have the potential to provide significant volumes (>100 million tons/year)	Develop/adapt dry corn stover analytical methods for diverse samples (>3) of another feedstock type (e.g. switchgrass) achieving mass balance closure of 100% $\pm$ 5%	Define the relationships between variations in the feedstock composition and key processing parameters	Develop/adapt dry corn stover analytical methods for diverse samples (>3) of another feedstock type (e.g. ensiled corn stover) achieving mass balance closure of 100% ± 5%	Define the relationships between variations in the feedstock composition and key processing parameters	Develop cost correlations for two other feedstocks based on the corn stover $1.07/gal baseline
Pretreatment	63% xylan yields and 13% sugar degradation in continuous reactor with > 30% solids from corn stover	1) Achieve 75% xylose yield in laboratory scale high solids pretreatment reactor on corn stem internode 2) Define the relationships between pretreatment conditions and the chemical/ultrastructural changes in corn stover stems that result in biphasic xylan hydrolysis	Validate > 75% xylan yield & < 8% degradation from corn stover using a continuous reactor	1) Understand sugar degradation kinetics & how to reduce degradation to < 6% for corn stover 2) Test accessory enzymes' effect on reducing pretreatment costs for corn stover in lab equipment	1) Achieve > 85% xylan yields and < 6% sugar degradation from corn stover using a continuous reactor with > 30% solids 2) Make final decision on pretreatment process to use in 2012 pilot operation	Provide bench scale pretreatment data on two other feedstocks (e.g. switchgrass, ensiled corn stover) to develop cost correlations against the corn stover baseline	Achieve >90% xylan to xylose & < 5% xylan degradation from corn stover in integrated pilot operation with > 30% solids
Hydrolyzate Conditioning	13% sugar losses in overliming conditioning step on corn stover		Define the relationships between corn stover hydrolyzate conditioning and fermentation performance in lab equipment	Reduce sugar losses in corn stover hydrolyzate conditioning step to < 7% in laboratory equipment (accessory enzymes is one option)	Reduce sugar losses in corn stover hydrolyzate conditioning step to < 2% in laboratory equipment	Provide bench scale conditioning data on two other feedstocks (e.g. switchgrass, ensiled corn stover) to develop cost correlations against the corn stover baseline	Reduce sugar losses in corn stover hydrolyzate conditioning step to < 1% in integrated pilot operation or eliminate need for conditioning
Enzyme Production	$0.32/gallon of ethanol	Develop the first generation computational model of CBH I capable of describing structure and function, and verify CBH I structure	1) Baseline commercial cellulases' specific activity 2) Determine how cellulase enzymes move along cellulose chains	Conduct targeted substitutions of cellobiohydrolase to increase specific activity by 2-fold relative to native	1) Define cellulase interactions at the plant cell wall 2) Validate the cost contribution of purchased enzyme at $0.16/gal EtOH	Validate the cost contribution of purchased enzyme at $0.10/gal EtOH	Validate a $0.10/gal cost contribution of purchased enzyme used in integrated pilot operation

Enzymatic Saccharification and Fermentation	> 85% Cellulose to EtOH, > 75% xylose to EtOH, 0% other sugars to EtOH in a total of 7 days in lab equipment with > 20% total solids from corn stover		Demonstrate > 85% cellulose to EtOH, > 80% xylose to EtOH, > 40% other sugars to EtOH in a total of 7 days in lab equipment with > 20% total solids	Define the relationships between lignin redeposition and enzyme kinetics	Demonstrate > 85% cellulose to EtOH, > 80% non-glucose sugar to EtOH in a total of 5 days in lab equipment with > 20% total solids	1) Demonstrate > 85% cellulose to EtOH, > 85% non-glucose sugar to EtOH in a total of 3 days in lab equipment with > 20% total solids 2) Develop bench scale SSF data on two other feedstocks (switchgrass, ensiled corn stover) to develop cost correlations against the corn stover baseline	Demonstrate > 85% cellulose to EtOH, > 85% non-glucose sugar to EtOH in a total of 3 days in integrated pilot operation with > 20% total solids
Integration/Modeling	Research state-of-technology utilizing current data and modeling shows a \$2.26/gal ethanol selling price with total capital of \$3.04/gal of annual installed capacity for corn stover		Complete rapid analysis method to predict component concentrations in pretreated slurry stream to same accuracy as wet chemistry methods	Completed biochemical pilot facility with 2 or more pretreatment trains and occupancy formally handed over to operating entity	1) Biochemical pilot facility shakedown completed (For NREL, demonstrated by successful operation of new pretreatment train(s) on corn stover) 2) Process cost estimate updated with latest data and engineering consultations	Provide equipment and operating costs for the corn stover \$1.07/gal baseline to develop cost correlations for 2 other feedstocks	Data from integrated pilot operation combined with process design & cost estimate validates a \$1.07/gal ethanol selling price and capital cost of \$1.85/gal of annual installed capacity for nth plant (adjusted to the current cost year from 2000\$) for corn stover

Figure E-2 shows a general process flow diagram of the $1.07/gallon target biochemical technology and the major barriers that must be addressed to accomplish the target. Appendix C provides the results of uncertainty analysis performed on the biochemical conversion process to understand the cost impacts of the technology barriers, associated targets, and other process parameters. In addition, financial and market parameters such as ROI and processing facility size were evaluated. From this information, a qualitative assessment of R&D and deployment risk can be made.

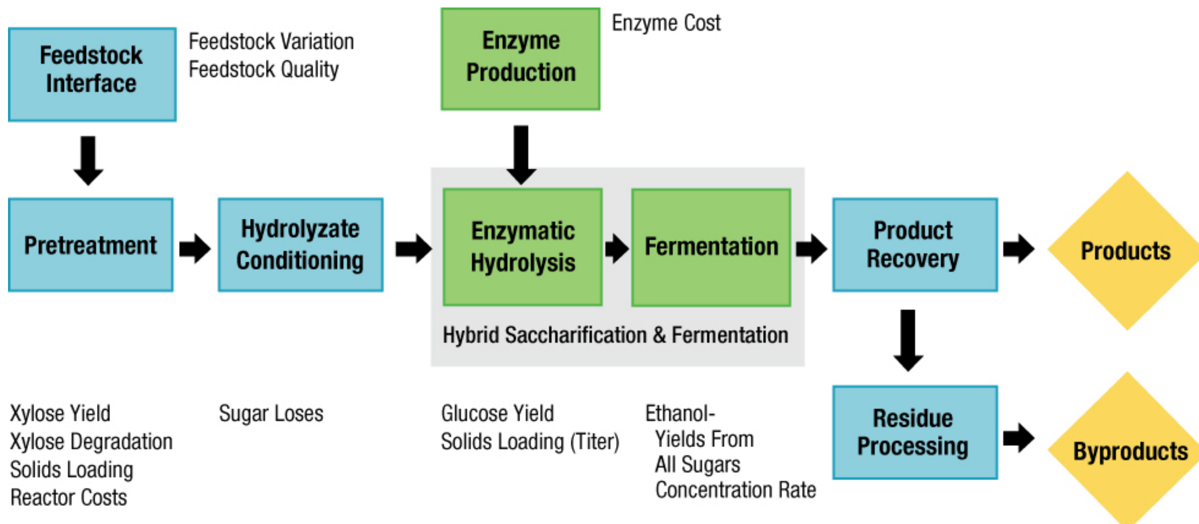


Figure E-2. Major Research Areas and Barriers for Biochemical $1.07/gallon Ethanol

E.1 Feedstock/Process Interface R&D Needs

Interface activities between feedstock development (assumed to be corn stover or a very similar feedstock for the $1.07/gallon target) and biochemical processing R&D will ensure the chemical and physical characteristics of the feedstock are optimized for the process and vice versa. Different types of feedstocks are likely to require different processing conditions but not necessarily new processes. Although corn stover will be used as the model feedstock, it will be necessary to adapt the conversion processes for the other feedstocks identified in the "Billion Ton" study to accomplish the 30x30 goal. To realize large-volume ethanol production, multiple feedstocks must be processed. This will require understanding the feed-process interactions, translating model agricultural residue feedstock data to other feedstocks, and identifying and working on new model feedstocks to cover other feedstock groups such as woody biomass.

The targets here are to determine the sensitivity of the overall process to differences in feedstock type and quality and determine how to adjust and modify the process to accommodate changes in feedstock.

Research will:

- Develop an understanding of the range of feedstock types expected to be used in pioneer plants
- Develop an understanding of and improve or make more suitable the quality (physical and chemical characteristics) of each feedstock through work with feedstock suppliers and researchers
- Determine the effects on all downstream unit operations of different feedstocks
- Develop an understanding of how to adjust the process to maintain optimal yields and productivities with varying feedstock quality or different feedstocks.

This is a relatively immature area of R&D, and specific targets need to be developed. Some important parameters and issues for the feedstock-process interface area include:

- Quality of the feedstock
    - How is carbohydrate content affected by formatting?
    - Do differences among feedstock fractions suggest different processing schemes?
    - Can digestibility or another aspect of feed be enhanced via a "pre-" pre-treatment?
- Cost of the delivered feedstock
    - What is the best trade-off between field processing and in-plant processing?
    - Can process limits, such as moisture in the feedstock, be managed with process requirements (minimum and maximum solids content)?
- Toxicity of the feedstock
    - Can acetyl groups be altered to reduce toxicity of feed during storage?
    - What compounds are created in storage practices such as ensiling?
- Handling in the processing facility
    - What equipment and manpower are required for the feedstock?

In relation to agricultural residues, this reveals several important considerations. Agricultural practices such as wet harvesting require different storage formats, and the conversion process must be able to accommodate these formats. For example, dry feedstock is generally straight from the field and undergoes minimal formatting other than baling or loafing. For this format, the most likely parameters important to the conversion process are quality and cost. Wet feedstock, however, may have been adapted via ensiling or other pre-processing methods, and as such, it may undergo maximum formatting before it arrives at the processing facility. The most likely important parameters for ensiled feedstock are quality, cost, handling, and toxicity.

E.2 Pretreatment and Hydrolyzate Conditioning R&D Needs

Pretreatment is a critical component of the biochemical conversion process, and it represents a significant cost component. The purpose of the pretreatment step is to generate a pretreated feedstock that is highly digestible in enzymatic hydrolysis and, in the case of dilute acid pretreatment, to convert a significant fraction of the hemicellulose to soluble sugars.

Although dilute acid pretreatment is a potential approach to achieving the process yields necessary to reach the $1.07/gallon target, recent advances in the understanding of plant cell wall structure and the hydrolytic enzyme system could allow for less severe and less costly pretreatment processes. In addition, hydrolyzates resulting from different feedstock and pretreatment approaches will have different conditioning requirements to allow for ethanologen performance that meets ethanol yield, rate, and concentration targets. Although significant advances have been made in pretreatment technology to increase sugar yields and decrease costs, additional advances are needed to achieve the $1.07/gallon target.

To achieve the 30x30 goal, a variety of biomass feedstock types—including agricultural residues, woody forest land residues, and herbaceous and woody energy crops—will be needed. With such a broad feedstock base, there is a range of compositional and structural features. The feedstock types respond differently to pretreatment processes and conditions, so experimental studies are needed to properly match feedstock types with pretreatment conditions and enzyme preparations. Parametric studies can help reveal these relationships to ensure that a variety of biomass feedstocks can be economically processed.

The target here is to maintain or increase the solids loading of 30% while increasing the xylan-to-xylose conversion to 90% and reducing the xylan lost to degradation products to 5% in a continuous, pilot-scale reactor.

Research will:

- Determine the location of xylan in the plant cell wall and optimize pretreatments that selectively remove and hydrolyze it to xylose
- Reduce sugar degradation to minimal levels by developing an understanding of the kinetic mechanisms that lead to undesirable degradation products and systematically blocking the pathways
- Make a down-selection to one primary pretreatment technology to focus research.

Knowledge of how specific pretreatment conditions and processes influence the reaction and re-arrangement of biomass feedstock components will enable cost-effective pretreatments that are properly matched to specific feedstock types and required enzyme activities and loadings. Cell wall imaging provides information about xylan, cellulose, and lignin location and reactivity to pretreatment methods, which enables the development of more targeted (i.e., efficient) pretreatments.

The target is to reduce the capital cost of pretreatment through the use of ancillary enzymes.

Research will determine if other enzymes, such as xylanases, can be used to improve xylose yields, minimize formation of degradation products, reduce costs associated with the pretreatment process by reducing the required severity, and reduce the need for conditioning.

Employing cost-effective hemicellulases and other accessory enzymes in conjunction with cellulases could allow for less severe and less costly pretreatment with lower sugar degradation losses and the ability to achieve a combined 90% xylose yield from pretreatment and enzymatic hydrolysis. A “hemicellulase/accessory enzyme” subcontract solicitation would engage commercial enzyme suppliers in the development and testing effort and include validation and knowledge transfer activities to ensure applicability to the biochemical process. Sugar degradation can also be addressed by developing an understanding of the kinetic mechanisms that lead to undesirable degradation products and then systematically blocking the pathways. Finally, parametric studies can determine relationships between sugar degradation and pretreatment conditions. The findings can be used to identify pretreatment conditions to reduce xylose degradation reactions to target levels.

The target here is to eliminate or greatly reduce the need for conditioning.

Research will develop an understanding of:

- The role of hydrolyzate conditioning to eliminate sugar losses
- Degradation kinetics to allow the minimization or elimination of the formation of inhibitory compounds.

A hydrolyzate conditioning step adds cost and complexity to the process and results in the potential loss of sugars for fermentation to ethanol. The need for conditioning is intrinsically related to the pretreatment process and conditions, which influence the formation of sugar degradation products that are potentially inhibitory and toxic compounds from lignin, portions of which could be solubilized under certain pretreatment conditions. A systematic approach that includes the release or formation of fewer inhibitory compounds during pretreatment and the development of more robust ethanologen strains is needed to eliminate the hydrolyzate conditioning step.

E.3 Enzyme Production R&D Needs

The enzymatic hydrolysis step saccharifies the cellulose found in energy plant cell walls to glucose using cellulase enzymes as part of simultaneous saccharification and co-fermentation (SSCF). As in the case of pretreatment, significant advances have been achieved in the enzymes used in this step over the past decade. An example is the recently achieved 30-fold reduction in enzyme cost. However, additional advances are required to achieve the $1.07/gallon target.

The target is to reduce the cellulase enzyme cost to $0.10/gallon of ethanol produced for a 90% conversion of cellulose to glucose within 3 days in a hybrid saccharification and fermentation (HSF) system.

Research will:

- Develop an understanding of cellulase interactions at the plant cell wall ultrastructural level to optimize hydrolysis processes and enzyme kinetics and, ultimately, cellulase use and cost
- Determine how cellulase enzymes move along the cellulose chain and the roles of enzyme sub-structures
- Employ targeted substitutions of enzyme components to increase specific activity, guided by molecular modeling of cellulase-substrate interactions
- Identify the enzyme production process and logistics that minimize processing and transportation costs of enzyme products.

To achieve the desired near-term cellulase cost reduction (a factor of approximately 2–5) scenario, further enzyme development work is critical (Xu 2006). This work is likely to follow the new and developing fields of protein engineering and include an even greater element of bioinformatics. The recently developed tools and databases that are now available to bioinformaticists show exciting potential to achieve the additional required 2 – 5 X cost reductions. Also, methods for conducting high-throughput directed evolution have been refined considerably over the past 2 years. Cellulases have been difficult to improve by directed engineering primarily because proper screens were not available. The adage “you get what you screen for” is especially true for such enzymes (Himmel and Georgiou 1993). Cellulases in the biorefinery must work on the complex structure of the cellulose buried deeply in the plant cell wall. Thus, conducting a robotic screening program on cellulose surrogates or modified celluloses usually leads to failure in the context of a biomass-degrading enzyme. Aspects of cellulase function to be improved by this program include cellulase-specific performance (e.g., bonds broken per unit of time per gram of enzyme), cellulase thermal tolerance, and cellulase resistance to substances found in biomass pretreatment hydrolyzates. Although there is yet no evidence that cellulose hydrolysis occurs more rapidly at elevated temperatures, the objective to increase the stability of cellulases to denaturation by increasing thermal tolerance is reasonable. Also, cellulases are known to be affected by high sugar concentrations, phenolics, and other extractives and sugar degradation products. Therefore, a program to increase the resistance of cellulases to these agents is likely to have a positive effect on the $1.07/gallon target. As part of this study, the enzyme companies are well placed to determine “best guess” scenarios for the costs and constraints to be expected for delivery and storage of improved process enzymes. This activity will likely target the non-informational approaches to improving enzyme economics. In addition, it will be necessary to understand cellulase interactions at the plant cell wall ultrastructural level to optimize hydrolysis processes and enzyme kinetics (Himmel, Ruth, and Wyman 1999).

Some key pieces of information are needed to enhance the effectiveness of near-term enzyme engineering activities. One is a direct measurement of the effectiveness of individual CBH I cellulase molecules acting on cell wall cellulose. To date, no direct experimental method permits such measurement, but this information is needed to assess the quality of enzyme engineering strategies (Zhang, Himmel, and Mielenz 2006). The complexity and structural uncertainty of real plant biomass is primarily responsible for this. New methods for imaging and measuring the rates of motion of these processive cellulases are needed. Computer modeling can also deliver important information about the mechanism of complex enzymes, such as CBH I (Nimlos et al. 2006, Matthews et al. 2006).

Although this work is likely to contribute primarily to the post-2012 objective, it is reasonable to expect some benefit to near-term enzyme engineering activities. One example of a near-term benefit is an understanding of the molecular basis for cellulose binding afforded by the cellulose binding domains, which are found in essentially all commercial-grade cellulases. Near-term activities designed to probe and map the cellulose binding domain binding affinities on cellulose (or the microfibril) for natural enzymes will permit design strategies for improving existing commercial enzyme components and ultimately reducing cellulase cost.

Lignin is known to migrate from its native configuration and compartmentalization during and immediately after application of thermal/chemical pretreatment processes such as dilute acid. The attempt to apply classical enzyme kinetics to assess the nature of the interference lignin poses for cellulase has not been especially useful for process engineers seeking to improve the pretreatment step or biochemists seeking to improve the tolerance of the enzymes. Again, the problem is the complexity of biomass. Classical kinetics provides only “ensemble average” information, and to improve this process, the actual cause for lignin-based enzyme inactivation must be determined at the molecular scale (Vinzant, Ehrman, and Himmel 1997). Once this level of understanding is obtained, pretreatment and enzyme use process parameters can be changed to minimize the deleterious impact released lignin has on remaining unit operations.

NREL’s Biomass Surface Characterization Laboratory affords new tools for this historical problem. New biomass surface imaging methods are being developed to permit the direct mapping of re-deposited lignin on pretreated biomass. Important directions to pursue include the development of lignin chemistry-specific molecular probes, which permit the visualization of lignins in plant cell walls, and probes for all the critical cell wall polymers, including the hemicelluloses and proteins (Matthews et al. 2006). Again, some of this work will continue past the 2012 target and build a foundation for the 2030 goal.

E.4 Enzymatic Saccharification and Fermentation R&D Needs

The development of an organism capable of producing ethanol from mixed biomass sugars at the required rates, yields, and titers to achieve the $1.07/gallon cost target is the biggest remaining technical challenge for biochemical conversion of biomass to ethanol. Significant advances in fermentation technologies must be achieved to meet the projected demand for 60 billion gallons of ethanol in 2030.

The target is to develop a robust, commercially viable biocatalyst (micro-organism) capable of fermenting 85% of the hemicellulose sugars and 95% of the glucose to a concentration of at least 6% ethanol in 3 days in a combined hybrid saccharification and fermentation (HSF) system.

Research will:

- Identify strain candidates that exhibit superior “wildtype” performance
- Use metabolomics, proteomics, and other tools to develop an understanding of metabolic bottlenecks in the carbon assimilation pathways that limit rates of pentose sugar uptake and the ability to withstand fermentation inhibitors such as organic acids, low pH, and increased temperature
- Extend “omics” studies to identify and aid understanding of secondary pathway limitations related to reaction co-factors and regulation of metabolism
- Increase pentose uptake rates by applying protein and metabolic engineering to increase sugar transporter efficiency, pentose specificity, and expression
- Improve strain robustness by manipulating cell membrane composition to reduce its permeability to organic acids and improve its temperature stability
- Use a combination of metabolic engineering, mutagenesis, and long-term culture adaptation strains on actual pretreatment hydrolyzate to achieve the target fermentation performance
- Perform parametric analysis of such factors as lignin re-deposition to minimize detrimental effects using structural and surface analysis tools.

Robust strains that ferment all hemicellulose sugars at high rates with minimum byproduct formation must be developed for commercial use. Improving the xylose-to-ethanol process yield (currently 25%–50%) to 85% is essential to meeting the $1.07/gallon target. Enhancement of the xylose fermentation rate is critical to achieving a high xylose-to-ethanol yield. The xylose fermentation rate needs to be enhanced 3- to 10-fold to approach the glucose fermentation rate. Reducing the toxic effect of inhibitors on pentose fermentation by improving microbial resistance to the hydrolysate or minimizing toxic levels during pretreatment and subsequent process treatment must also be achieved. Improved microbial resistance can be achieved by traditional adaptation or a more rational approach using advanced biological tools. It would be beneficial to develop an understanding of the toxic mechanisms to help in the development of superior strains and to provide guidance in the pretreatment process.

The application of effective metabolic engineering tools is critical to meeting the $1.07/gallon target in 2012. One challenge is to develop better cost estimates of current best fermentation organisms. Such performance data are generally not publicly available. Current plans are to conduct a “fermentation organism” solicitation, similar to the enzyme subcontracts, to develop and validate the performance of this organism.

The “fermentation organism” solicitation will encourage industry, academic research organizations, and national laboratories to work together to overcome the technical barriers that limit current strain performance. Research breakthroughs and innovative approaches are critical to this goal. Parallel efforts with the industry-driven organism solicitation and fundamental toolbox building (core R&D) will ensure success. Capabilities built by the Biomass Program at the national laboratories can contribute to the fundamental toolbox building significantly. Concerted, multi-year efforts will be crucial.

The development of robust, industrially useful fermentation strains to meet these targets will require substantial knowledge of the fundamental factors that limit efficient sugar bioconversion in hydrolysate. A collective knowledge of strain improvement—including a deeper understanding of strain physiology, metabolic engineering options, hydrolysate toxicity, and process considerations—is required.

The target is to develop an HSF process capable of saccharifying 90% of the cellulose to glucose and fermenting 85% of the hemicellulose sugars and 95% of the glucose to ethanol in 3 days while maintaining the solids concentration necessary for the ethanol concentration target above.

Research will:

- Use information about the enzyme capabilities and fermenting strain's performance to develop and test strategies for efficiently integrating enzymatic hydrolysis with biomass sugar fermentation to maximize cellulose hydrolysis and sugar fermentation rates and yields
- Quantify the effect of enzyme loading, strain inoculation time, and inoculum charge on batch process performance
- Use reactor designs and operational schemes to maximize the solids loading and conversion of cellulose and other sugars to ethanol.

Working in a solids environment presents special challenges for organisms. To meet the $1.07/gallon target, an organism must be able to ferment hydrolysate with a minimum total solids content of 20% (with 11%–15% total sugars), with minimal nutrient supplement and hydrolysate conditioning. A tolerance to at least 5% ethanol, and preferably to 8%–10% (w/w), is needed to achieve higher ethanol titer.

Improving the pentose fermentation rate in hydrolysate, as described above, is key to shortening fermentation time. Enhancing the enzyme activity (enzymatic hydrolysis by cellulases and hemicellulases) and the organism's tolerance to hydrolysates will also contribute to the residence time reduction goal.

The organism must be produced at low cost via onsite production with hydrolysate sugars and minimal nutrients or supplied at low cost (pennies per gallon of ethanol), as in the corn ethanol industry. Inhibitors in hydrolysate, such as acetic acid, can severely inhibit cell growth, so overcoming such growth inhibition is critical.

Enhancement of the specific productivity of the fermentation organism, particularly on xylose and arabinose, is necessary to keep the inocula at acceptable cost levels. This is critical to achieving ethanol productivity using industrial-size inocula to achieve the $1.07/gallon target. Cell recycle may not be an option in biomass hydrolysate fermentation because of the lignin residue after fermentation.

E.5 Integration/Process Engineering R&D Needs

Combining individual unit operations into an integrated, systematic process is a significant challenge. Individual pilot-scale operations that demonstrate performance of unit operations and complete, integrated pilot development runs will be required to demonstrate the $1.07/gallon technology. A specific challenge will be to continue to demonstrate high solids processing at the pilot scale to reduce capital costs throughout the process (at least 30% in pretreatment and 20% in hydrolysis).

The targets are to:

- Optimize the key unit operations, pretreatment, hybrid saccharification and fermentation, product recovery, and residue processing (separations only) in an integrated pilot plant with appropriate recycles
- Obtain the data necessary to update the conceptual process design and cost estimate to validate the 2012 technical target.

Research will:

- Set up all appropriate unit operations in a safe, integrated system capable of continuous operation, 24 hours per day, 7 days per week, with data-gathering capabilities
- Develop analytical methods and equipment to monitor the process and collect data
- Test the integrated process and optimize conditions to maximize performance
- Use data from the operating pilot plant to complete a conceptual full-scale process design and cost estimate to validate the 2012 technical target.

Integration work needs to continue efforts to advance core process knowledge, with an emphasis on understanding the factors that affect integrated process performance and produce process-relevant residues and waste streams for testing. Ultimately, this research reduces risk as well as capital and operating cost by overcoming technical barriers associated with high-solids processing, developing an understanding of the effects of feedstock variability, and developing a better understanding of the key interactions that control process efficiency and performance (process integration).

Following adequate bench-scale testing, the integrated process must be tested at the pilot scale (1 ton of dry biomass/day). It is envisioned that one to three feedstocks—such as stover, switchgrass, and wood chips—could be run through available pilot systems. Data collected from bench and pilot runs will be used to assess the state of technology annually.

Additional work is needed to improve and further develop analytical methods to facilitate research efforts that require accurate compositional information. Realizing the goals of the 30x30 initiative will require the development, standardization, and validation of hundreds of new analytical methods specifically for biomass feedstocks and intermediate process streams. The data generated by these analytical methods will be used to obtain performance information to accurately evaluate process economics. This will improve the efficiency of R&D activities in the biomass community and support the emerging industry needs for accurate and rapid analysis methods for quality monitoring and process control.

Specific activities are to:

- Develop and validate standardized wet chemical methods for analysis of biomass feedstocks and intermediate products
    - Develop improved analytical methods that more accurately quantify biomass-derived components in the liquid phase
    - Complete development of analytical methods for analysis of corn stover that accurately quantify more than 97% of its dry mass
    - Develop compositional analysis methods for a new near-term feedstock (e.g., switchgrass or other material) that accurately quantify more than 97% of its dry mass
    - Publish industry-wide consensus standards
- Develop and validate low-cost, rapid compositional analysis methods to support research efforts and facilitate online compositional measurements required for quality monitoring and process control
    - Develop rapid analysis methods for a new near-term feedstock
    - Develop rapid analysis methods for liquid and solid components in intermediate process streams.

Process design is a critical part of technology development. Without it, the technology pieces are just individual operations. By incorporating process design, standard engineering methodology, and economic analysis techniques into an R&D plan, the resulting work is targeted to create a cost-effective, technically viable process.

A large body of work has already been developed to direct biomass R&D efforts. Including process engineering and analysis in R&D provides:

- Quantification of the critical targets and activities
- Development of intermediate metrics that contribute to the critical targets
- Progress tracking to the targets via annual state-of-technology assessments
- An understanding of uncertainty in process parameters and the resulting cost effect
- Early feasibility evaluation of alternate processes that might improve the process economics/feasibility.

Table E-2 shows an example of the progress that could be achieved against each technology target in the biochemical process for $1.07/gallon ethanol. For simplicity, one “path to get there” has been identified for the process design and economic analysis. This does not mean that if the listed targets are not met or this specific process design is not piloted that target cannot be achieved. Other targets may be exceeded, or other process designs (e.g., an alternate pretreatment) may become viable before 2012. A fluid design and analysis scheme must be employed to allow these breakthroughs. It is also important to recognize that R&D rarely progresses linearly and improvements are likely to come in a more step-wise fashion.

Table E-2. Possible Interim Targets to $1.07/Gallon Ethanol for Stover

	2005 Post Enzyme-Subcontract	2007	2008	2009	2010	2011	2012 Market Target
Minimum Ethanol Selling Price	$2.26						$1.07
Installed Capital per Annual Gallon	$3.04						1.85
Yield (Gallon/dry ton)	65						90
Feedstock							
Feedstock Cost ($/dry ton)	$53		$45				$35
Pretreatment							
Solids Loading (wt%)	30%	30%	30%	30%	30%	30%	30%
Xylan to Xylose	63%	68%	72%	77%	81%	86%	90%
Xylan to Degradation Products	13%	12%	10%	9%	8%	6%	5%
Conditioning							
Xylose Sugar Loss	13%	11%	9%	7%	4%	2%	0%
Glucose Sugar Loss	12%	10%	8%	6%	4%	2%	0%
Enzymes							
Enzyme Contribution ($/gal EtOH)	$0.32	$0.32	$0.32	$0.32	$0.16	$0.10	$0.10
Saccharification & Fermentation							
Total Solids Loading (wt%)	20%	20%	20%	20%	20%	20%	20%
Combined Saccharification & Fermentation Time (d)	7	7	7	6	5	3	3
Overall Cellulose to Ethanol	86%	86%	86%	86%	86%	86%	86%
Xylose to Ethanol	76%	76%	76%	80%	80%	80%	85%
Minor Sugars to Ethanol	0%	40%	40%	40%	80%	80%	85%

To understand how much development is still required, DOE/NREL tracks the research state of technology of the biochemical conversion process by extrapolating current-year laboratory results to a conceptual process design and cost estimate. The design and cost estimates are based on engineering company consultations and ASPEN modeling (Aden et al. 2002). The state of technology includes only ethanol and excess electricity sales (i.e., no co-product credits). It does not include any proprietary, company-specific enhancements over the baseline conversion technology demonstrated at DOE's core biomass research program.

Figure E-3 shows state of technology advances from 2001 to 2005 and looks to the future with R&D targets to understand what is required to achieve the technical target in 2012. Much of the cost reductions from 2001 through 2005 were because of DOE-industry partnerships formed to reduce the cost of enzymes (Harris, Teter, and Cherry 2006; Mitchinson 2006). As shown in the figure, the 2012 target was accelerated by DOE to accommodate the president's Advanced Energy Initiative. The research outlined here addresses the more aggressive target.

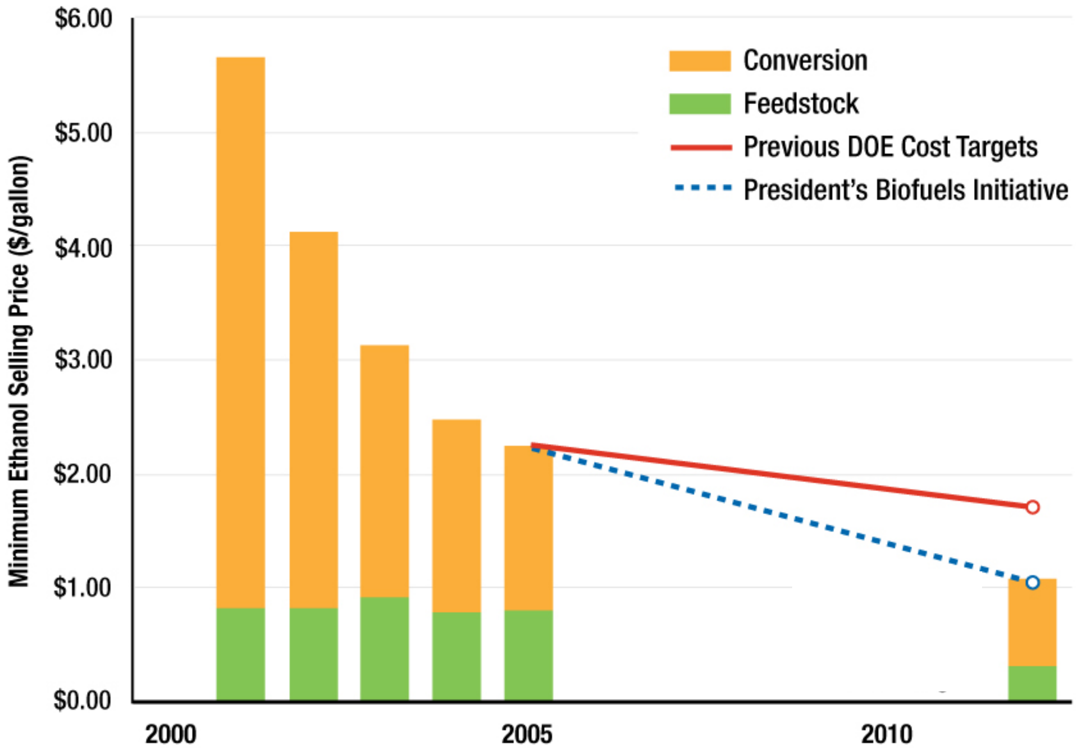


Figure E-3. Research State of Technology for Biochemical Conversion

Appendix F: Thermochemical Conversion

F.1 Gasification Scenarios for the $1.07/Gallon Ethanol Cost Target

The target of $1.07/gallon thermochemical ethanol by 2012 was evaluated by constructing process models based on currently available technologies to benchmark a state-of-technology case. The process design for ethanol via gasification/mixed alcohol synthesis is documented in the draft Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass design report (Phillips et al. 2007). Techno-economic analyses provide a biofuel production cost based on capital and operating cost estimates for individual unit operations in the mixed alcohol process design. A sensitivity analysis helps identify variables and, thus, R&D areas that, when overcome, have the largest effect on the cost of thermochemical ethanol. The thermochemical ethanol cost estimates are based on the process design parameters summarized in Figure F-1 and listed in Table F-1. A more detailed view of the process is shown in Figure F-2.

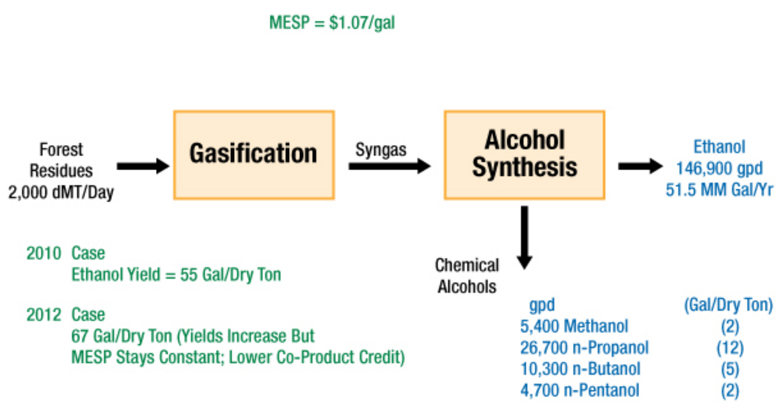


Figure F-1. Process for Thermochemical Ethanol Production at $1.07/gallon

Table F-1. Thermochemical Ethanol Production From Biochemical Lignin-Rich Residues and Forest and Wood Residues: Path to $1.07/Gallon Ethanol

	2002	2005	2008	2010	2012
Process Description	Tar Removal & Disposal	Tar & Light Hydrocarbon Reforming	Tar & Light Hydrocarbon Reforming — Increased Hydrocarbon Conversion	Consolidated Tar & Light Hydrocarbon Reforming	Improved Alcohol Catalysis & Synthesis
Minimum Ethanol Selling Price ($/gal ethanol)	$2.41	$1.98	$1.73	$1.55	$1.07
Higher Alcohol Co-Product Value ($/gal alcohol)	$1.15	$1.15	$1.15	$1.15	$1.15
Installed capital cost ($/annual gal MA)	$4.42	$2.97	$2.75	$2.66	$1.97
Operating cost ($/annual gal MA) Excluding Feed and CoProduct	$0.41	$0.47	$0.37	$0.30	$0.24
Ethanol Yield (gal/dry ton)	64.5	62.7	65.1	66.1	75.8
Mixed Alcohol Yield (gal/dry ton)	75.9	74.0	76.7	77.9	89.1
Feedstock					
Feedstock Price ($/dry ton)	$53	$53	$45	$45	$35
Thermochemical conversion					
Syngas yield (lb/lb dry feed)	0.82	0.82	0.82	0.82	0.82
Raw syngas methane (mol% - dry basis)	15.09	15.09	15.09	15.09	15.09
Cleanup and Conditioning					
Tar reformer exit methane (mol% - dry basis)	N/A	13.5	4.39	1.19	1.38
Tar reformer light HC reforming - % CH4 conversion	N/A	20%	50%	80%	80%
Tar reformer heavy HC reforming - % benzene	N/A	70%	90%	99%	99%
Tar reformer heavy HC reforming - %tar conversion	N/A	95%	97%	99.9%	99.9%
SMR Light HC reforming - % CH4 conversion	85%	NA	NA	NA	NA
Sulfur removal	1ppmv (SMR)	50 ppmv(MA)	50 ppmv(MA)	50 ppmv (MA)	50 ppmv (MA)
Catalytic Fuel Synthesis					
Compression for fuel synthesis (psia)	2,000	2,000	2,000	2,000	1,000
Single pass CO conversion	40%	40%	40%	40%	60%
Overall CO conversion	40%	40%	40%	40%	60%
CO selectivity to alcohols (CO2-free basis)	80	80	80	80	90

Biomass gasification is a complex thermochemical process that consists of a number of elementary chemical reactions. It begins with the thermal decomposition of a lignocellulosic fuel which is followed by partial oxidation of the fuel with a gasifying agent—usually air, oxygen, or steam (Tabatabaieraissi and Trezek 1987). The initial heating of the biomass leads to water evaporation. A further increase in temperature initiates biomass pyrolysis, which is followed by the partial oxidation of pyrolysis vapors. The char remaining after a biomass particle is devolatilized is also gasified.

The biomass gasification product gas is a low- to medium-energy-content gas (depending on the gasifying agent) that consists mainly of carbon monoxide, hydrogen, carbon dioxide, water, nitrogen, and hydrocarbons. Minor components of the product gas include tars, sulfur and nitrogen oxides, alkali metals, and particulates. These minor components potentially threaten the success of downstream syngas use.

Gas composition and quality are dependent on a range of factors, including feedstock composition, type of gasification reactor, gasification agents, stoichiometry, temperature, pressure, and the presence or lack of catalysts. The energy content of the gasification product gas ranges from 5 MJ/Nm^3 to 15 MJ/Nm^3 and is considered a low- to medium-energy-content gas compared with natural gas (at 35 MJ/Nm^3) (Littlewood 1977; Maschio, Lucchesi, and Stoppato 1994). The relative amount of carbon monoxide, carbon dioxide, water, hydrogen, and hydrocarbons depends on the stoichiometry of the gasification process and the selected gasification medium. The air-fuel ratio in a gasification process generally ranges 0.2–0.35, and if steam is the gasifying agent, the steam-biomass ratio is less than 1. If air is used as the gasifying agent, then roughly half of the product gas is nitrogen gas (De Bari et al. 2000).

Air-blown, or directly heated, gasifiers use the exothermic reaction between oxygen and organics to provide the heat necessary to devolatilize biomass and convert residual carbon-rich chars. In directly heated gasifiers, the heat that drives the process is generated within the gasifier. Thus, when air is used, the product gas is diluted with nitrogen and typically has a dry-basis calorific value of about 5–6 MJ/Nm^3. The dry-basis calorific value of the product gas can be increased to 13–14 MJ/Nm^3 through the use of oxygen instead of air. Oxygen production is expensive, however, and its use has been proposed only for direct-heating gasification applications that involve the production of synthesis gas when nitrogen is not permitted in downstream synthesis conversion operations. Oxygen-blown gasifiers typically operate at high pressures (~30 bar), similar to the outlet delivery of the air separation unit.

Indirectly heated gasifiers accomplish biomass heating and gasification through heat transfer from a hot solid or through a heat transfer surface. Because air is not introduced into the gasifier, little nitrogen diluent is present, and a medium calorific gas is produced. Dry basis values of 18–20 MJ/Nm^3 are typical.

Gas phase impurities in syngas include ammonia, hydrogen cyanide, other nitrogen-containing gases, hydrogen sulfide, other sulfur gases, hydrogen chloride, alkali metals, organic hydrocarbons (tar), and particulates. The concentration of these non-syngas components depends on feedstock composition. For example, gasification of biomass with high nitrogen and sulfur content yields high levels of ammonia and hydrogen sulfide in the syngas stream. Hydrogen chloride concentration in biomass-derived syngas directly correlates to the chlorine content of the feedstock. Alkali metal, mostly potassium, in syngas is related to the alkali content in the biomass ash. Ash particles entrained in syngas affect the alkali metal content of syngas. The concentration of alkali vapors or aerosols in syngas depends on the ash chemistry of the selected biomass feedstock and the temperature of the gasification process.

The organic impurities in syngas range from low-molecular-weight hydrocarbons to high-molecular-weight polynuclear aromatic hydrocarbons. The lower-molecular-weight hydrocarbons can be used as fuel in gas turbine or engine applications, but they are undesirable for mixed-alcohol synthesis. The higher-molecular-weight hydrocarbons are collectively known as “tar.” Tar yields in biomass-derived syngas can range from 0.1% (downdraft) to 20% (updraft) or greater (pyrolysis).

F.2 Syngas to Mixed Alcohols (Ethanol)

Mixed alcohols are an attractive gasoline blending stock for octane enhancement or as a fuel because they have better fuel properties than methanol and can use the existing fuel infrastructure. Several companies rigorously pursued the commercial development of mixed alcohol synthesis in the 1980s and early 1990s; however, no commercial mixed alcohol synthesis from syngas plants are currently operating. The commercial success of mixed alcohol synthesis has been limited by poor selectivity and low product yields. Single-pass yields are on the order of 10% syngas conversion to alcohols, with methanol typically being the most abundant alcohol (Wender 1996; Herman 2000). Commercialization efforts were largely discontinued because of the low-cost petroleum available at the time, which led to unfavorable process economics. Current economic conditions—in which crude oil is around $60/barrel and natural gas prices around $7–$9/MMBtu, make mixed alcohols from biomass-derived syngas an attractive renewable blending stock for transportation fuels.

R&D has shown that methanol can be recycled to produce higher alcohols or removed and sold separately. To date, modified methanol and modified Fisher-Tropsch catalysts have been more effective in the production of mixed alcohols; the sulfide-based catalysts tend to be less active than the oxide-based catalysts (Herman 2000). For an economic commercial process, improved catalysts are needed to increase the productivity and selectivity to higher alcohols (Fierro 1993).

Techno-economic analyses of thermochemical ethanol scenarios show that the separation of the higher alcohols (e.g., n-propanol, n-butanol, and n-pentanol) from the mixed alcohol product to enable selling them into their respective chemical markets (Phillips et al., 2007) could provide the initial economic benefit to accelerate the deployment of thermochemical technologies by making the first plants more economically attractive.

The thermochemical route to ethanol and other mixed alcohols is depicted in Figure F-2.

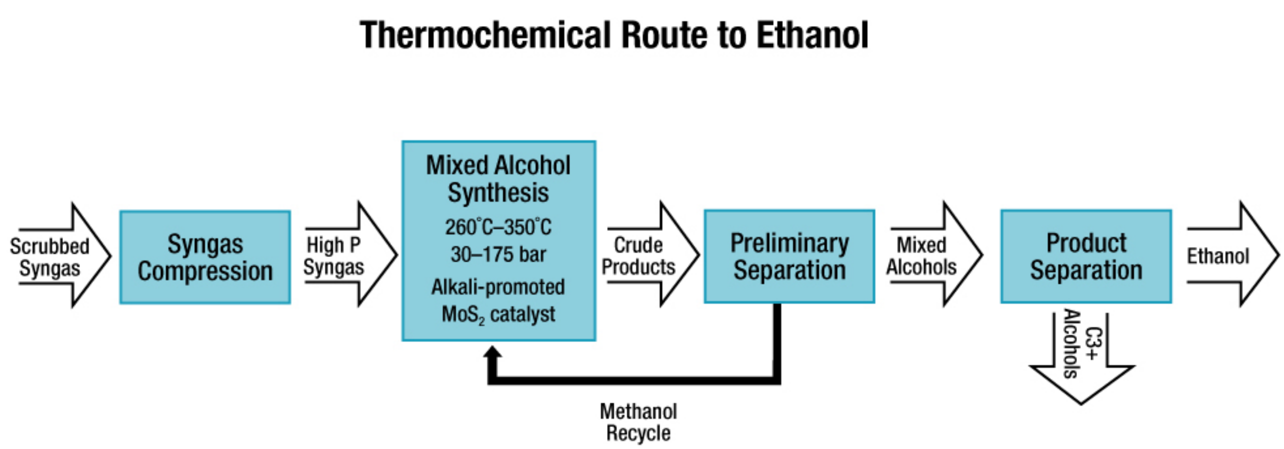


Figure F-2. Block Flow Diagram of Syngas Conversion to Mixed Alcohols

The capital cost breakdown for the major process areas is shown in Table F-2.

Table F-2. Capital Investment Distribution of Major Process Areas

Process (From Figure F-1)	% of Total Capital Cost
Syngas Production	**50%**
Mixed Alcohol Synthesis	**29%**
Carbon Dioxide Removal	**17%**
Product Fractionation	**4%**

Table F-3 shows the market volume and market price for each alcohol co-product. Assuming a 3% per year market growth in 2012, it would take close to 10 plants to saturate the market for n-propanol and n-pentanol. As the number of plants increases, the options for other uses of the co-product alcohols will need to be investigated. Other uses include recycling of the co-product alcohols to the synthesis reactor, using the co-product alcohols internally as fuel for steam and power, and using the entire ethanol and co-product alcohol stream as a transportation fuel.

Table F-3. Alcohol Co-Product Market Size

Alcohol	2001 Market Volume (Thousand Tonnes/Year)[(a)]	2001 Market Price ($/Gallon)[(b)]	In 2012 % of Market for One Plant at 2,000 Tonnes/Day	In 2012 % of Market for Ten Plants at 2,000 Tonnes/Day
Methanol	31,000	$0.60	0.01%	0.1%
n-Propanol	142	$3.69	13%	133%
n-Butanol	1,226	$3.72	3%	30%
n-Pentanol	35	$4.23	10%	95%

(a) Bizzari, Gubler, and Kishi 2002.
(b) Bain (2005).

In a recent review of mixed alcohol synthesis processes (Spath and Dayton 2003), the cost of mixed alcohols from natural gas-derived syngas ranged $0.50–$1.20/gallon, depending on the process assumptions and the cost of natural gas. Improved catalyst yield and selectivity, better process integration (to reduce energy losses), and economies of scale will improve overall process economics and opportunities. These technical and economic barriers need to be addressed by R&D efforts aimed at demonstrating integrated biomass gasification, gas cleanup and conditioning, and high-pressure catalytic synthesis of mixed alcohols.

Other R&D efforts led to the pilot-scale demonstration of several processes to convert syngas derived from natural gas to mixed alcohols.

- A 12,000-ton/year facility based on the partial oxidation of natural gas to make syngas converted in a fixed-bed adiabatic reactor charged with a modified methanol synthesis catalyst was built in Italy in 1982 (Olayan 1987) as a result of a joint venture between Snamprogetti and Haldor Topsoe.
- In 1984, Dow Chemical developed a process based on a novel alkali-promoted molybdenum disulfide catalyst that is inherently resistant to sulfur poisoning. Gas cleanup and conditioning requirements for syngas used in this process should be less stringent compared with those of other catalytic conversion processes.
- The Octamix process developed by Lurgi was based on a modified low-pressure methanol synthesis catalyst and demonstrated in a 2-ton/day plant built in May 1990 at the Institute of Energy Process Engineering at the Research Centre in Julich, Germany.

F.3 R&D to Achieve Syngas-to-Ethanol Cost Targets

The following sections provide detailed descriptions of the R&D activities presented in Table F-1.

F.3.1 2002: Tar Removal and Disposal

The 2002 case presents thermochemically derived ethanol prior to tar destruction, gas cleanup, and conditioning research. Without gas cleanup and conditioning for tar removal, the gasification system removes tars and other contaminants (e.g., ammonia, alkalis, and residual particulates) via water quench. [A high-pressure gasification system might consider a physical solvent such as Rectisol instead, but it is unknown whether a physical solvent can remove the tars to a low enough level (Nexant 2005). Plus, operational problems such as foaming are known to occur from hydrocarbons in the physical solvent.] The tars are entrained in the scrubber water, which must be treated and disposed of. This increases capital and operating costs. In addition, ethanol yield is reduced because of the loss of hydrocarbon tar components. More downtime is required to clean the tars from the heat exchange and cooling systems, so the operating capacity factor is lower. The lighter hydrocarbons are converted to carbon monoxide and hydrogen using conventional SMR.

F.3.2 2005–Present: Sequential Tar and Light Hydrocarbon Reforming

Clearly, the physical removal of tar from biomass-derived syngas is economically and environmentally unattractive. Therefore, the 2005 state-of-technology design incorporates sequential tar and light hydrocarbon reforming to separately convert the heavy (tar) and light hydrocarbons to additional syngas. In this design, a fluidized bed tar reformer is placed downstream of the gasifier to convert tars and other hydrocarbons in the raw syngas to carbon monoxide and hydrogen.

The tar reformer unit operation works well for tar reforming, but it has not been validated experimentally to efficiently reform light hydrocarbons. This un-optimized tar reformer converts only 20% of methane, so an additional SMR step is required downstream. This is still an improvement over the 2002 case because the capital and operating costs of this system are less—primarily because the reduced tar loadings mean a smaller quench system is needed. In addition, there is a reduction in waste water. Alcohol yields are also slightly higher because the tars are converted to additional syngas.

F.3.3 2008 Target: Improved Sequential Tar and Light Hydrocarbon Reforming

Clearly, capital and operating costs can be reduced if tars and light hydrocarbons can be converted in a single unit operation. This is an intermediate cost goal on the way to achieving tar and light hydrocarbon reforming in one step. In this case, methane conversion increases from 20% to 50% in the fluid bed tar reformer, benzene conversion is increased from 70% to 90%, and tar conversion is increased from 95% to 97%. This results in a decrease in capital and operating costs because of a reduction in the size and energy requirements of the downstream SMR.

F.3.4 2010 Target: Consolidated Tar and Light Hydrocarbon Reforming

The 2010 design represents the R&D goal of consolidated tar and light hydrocarbon reforming. For this case, the tar reformer changes from a single fluidized bed to a two-vessel circulating tar reformer/catalyst regenerator system. This is to maintain optimum catalyst reforming activity and maximize tar and hydrocarbon conversion efficiency. In this system, tar conversion increases to 99.9%, benzene conversion increases to 99%, and methane conversion increases to 80%. Because methane conversion is essentially as high as the conversion for the conventional SMR step, the SMR can be eliminated from the process design.

This case is the basis for the R&D activities to develop fluidizable tar-reforming catalysts for demonstration in integrated biomass gasification systems.

F.3.5 2012 Target: Consolidated Tar and Light Hydrocarbon Reforming plus Improved Alcohol Catalysis and Synthesis

The deployment of thermochemical ethanol technologies can begin after consolidated gas cleanup and conditioning technology is demonstrated to generate a clean syngas suitable for fuels synthesis. Therefore, the 2012 design presents incremental process improvements to optimize synthesis catalyst performance to increase ethanol/mixed alcohol yields.

The advances in catalysis and alcohol synthesis result in an increase in mixed alcohols single-pass carbon monoxide conversion from today's value of 38.5% to 50%. In addition, the carbon monoxide selectivity to alcohols increases from 80% to 90%, and the alcohols synthesis pressure is reduced from 2,000 psia to 1,000 psia. The product yield increases by 12 gallons/dry ton. The energy requirement is reduced because, in addition to a lower syngas pressure for alcohol synthesis, less unconverted syngas is recompressed and recycled. All of this contributes to a reduction in overall capital cost.

F.4 Technical Barriers to Achieving the Syngas-to-Ethanol Cost Targets

To facilitate the development of advanced thermochemical conversion systems in gasification, advanced R&D is needed to address technical barriers. The technical approach for the OBP thermochemical platform involves core research to address identified technical barriers. This leads to demonstration in integrated biorefineries, which, in turn, leads to commercialization.

A conceptual block-flow diagram of thermochemical conversion is depicted in Figure F-3. Each technical barrier area has technology options. R&D plans are being developed to overcome these barriers and achieve low-cost biofuel production to meet the 30x30 goal.

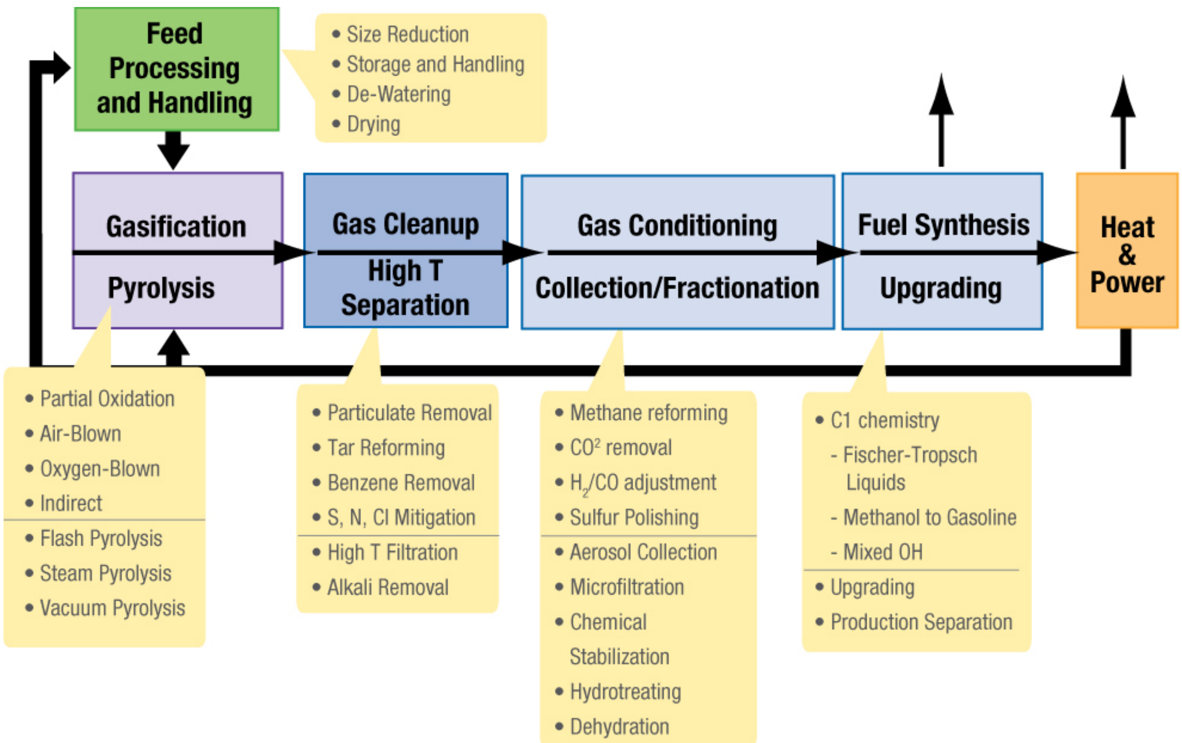


Figure F-3. Conceptual Block Flow Diagram of Thermochemical Conversion Technical Barriers

F.4.1 Feed Processing and Handling

For biorefineries, it is important that feedstock requirements be met while preparation requirements are minimized to reduce costs. This will require balancing the cost of plant-gate feedstock with the handling and processing required for reliable operation. The objective is to develop methodologies that allow biomass to be collected, prepared, and converted in a cost-effective manner.

Although specific R&D activities to supply biomass feedstocks to integrated biorefineries at specified cost targets are covered in Appendix D, feedstock processing as it relates to the thermochemical conversion process will need to be addressed. In the wide application of biomass, feedstocks such as forest and wood residues must be compatible with thermochemical processing technologies. Also, the use of wet residues requires appropriate pretreatment for de-watering and drying useable particle-size materials (for gasification and pyrolysis systems). This becomes an even greater challenge for pressurized gasification systems. To address this barrier, refinements in dry biomass feeder systems for use with gasification and pyrolysis will be required.

F.4.2 Thermochemical Processing

The crucial first step in the R&D process is to resolve technical questions related to the operability and reliability of biomass gasification systems. Fundamental gasification studies, process modeling, and techno-economic evaluations will help identify opportunities for technology improvements. Research, development, and deployment (RD&D) on advanced gasification technologies for long-term applications will lead to lower-cost, more efficient, cleaner gasification systems appropriate for a variety of biomass feedstocks.

F.4.3 Cleanup and Conditioning

Techno-economic analysis has shown that syngas cleanup and conditioning to remove chemical contaminants such as tar, ammonia, chlorine, sulfur, alkali metals, and particulates has the greatest effect (the potential for a 28% ethanol cost reduction) on the cost of clean syngas. To date, gas cleanup and conditioning technologies are unproved in integrated biorefinery applications.

R&D activities are addressing catalytic gas cleanup and conditioning strategies to produce a clean syngas from a range of biomass feedstocks and the validation of syngas quality suitable for mixed alcohol synthesis. These R&D activities are being pursued to validate the cost targets determined from the techno-economic analyses of the thermochemical ethanol scenarios via gasification/mixed alcohol synthesis.

The target conversions for impurities in biomass-derived syngas are listed in Table F-4. The table presents the 2005 state-of-technology case and the 2010 tar-reformer goal case. The conversion percentage for current performance is what can be achieved in the laboratory for short time periods prior to catalyst deactivation. The goal case conversions were selected to yield an economically viable, clean syngas that is suitable for use in a catalytic fuel synthesis process without further hydrocarbon conversion steps.

Table F-4.Tar Reformer Performance – % Conversion

Compound	Current	Goal
Methane (CH_4)	20%	80%
Ethane (C_2H_6)	90%	99%
Ethene (C_2H_4)	50%	90%
Tars (C10+)	95%	99.9%
Benzene (C_6H_6)	70%	99%
Ammonia (NH_3)	70%	90%

"Gas conditioning" is a general term for removing the unwanted impurities from biomass gasification product gas. It generally involves an integrated, multi-step approach that depends on the end use of the product gas. The goal is to demonstrate catalytic gas cleanup and conditioning strategies to produce a clean syngas from a range of biomass feedstocks and validate the syngas quality for mixed alcohol synthesis. For this report, the focus is on removing or eliminating tars without regard to acid gas, ammonia, alkali metal, and particulate removal.

R&D activities related to cleanup and conditioning of intermediates from thermal processing of biomass include:

- Evaluating the chemistry and kinetics of biomass gasifier tar destruction
- Examining catalytic reforming of tars
- Analyzing large-scale gas conditioning with catalysts
- Developing advanced systems for clean gas production through the use of membranes and circulating fluid beds of catalyst/adsorbant
- Developing advanced concepts for particulate and tar removal in existing test-bed facilities
- Developing options for new thermal and catalytic removal and treatment technologies and materials.

One promising hot gas conditioning method for tar destruction is catalytic steam reforming. Catalytic steam reforming offers several advantages:

- Catalyst reactor temperatures can be thermally integrated with the gasifier exit temperature.
- The composition of the product gas can be catalytically adjusted.
- Steam can be added to the catalyst reactor to ensure complete reforming of tars.

Hot gas conditioning using current or future commercially available catalysts offers the best solution for mitigating biomass gasification tars. Tars are eliminated, methane can be reformed if desired, and the water-to-carbon monoxide ratio can be adjusted in a single step.

Research is expected to improve gas cleaning and conditioning to allow biomass syngas to be effectively used for liquid fuels production.

F.4.4 Tar Reforming Catalyst Development

Improvements in tar reforming catalyst performance and long-term activity following many deactivation-regeneration cycles are being investigated. Fundamental catalyst studies are being performed to determine deactivation kinetics and mechanisms by probing catalyst surfaces to uncover molecular-level details. Combining this fundamental information should lead to improved catalyst formulations on robust support materials.

Alternative tar reforming catalysts are being developed in ongoing projects at several institutions with the goal of improving catalyst performance to realize consolidated tar and light hydrocarbon reforming. The Gas Technology Institute is using a novel submerged combustion melting technology developed for the glass industry to generate engineered catalysts by inserting catalytically active metals into olivine crystal structures. The Research Triangle Institute is developing attrition-resistant tar reforming catalysts by impregnating zeolites structures with active metals and testing them in a laboratory-scale integrated cleanup and conditioning unit called the Therminator. NREL is developing fluidizable, attrition-resistant reforming catalysts by depositing active metals onto the surface of hardened alumina spherical substrates.

Optimized catalyst formulations and materials are also being evaluated at the pilot scale at NREL to demonstrate catalyst performance and lifetime as a function of process conditions and feedstock. The goal of these efforts is to provide chemical and engineering data to enable the design and successful demonstration of a regenerating tar-reforming reactor for long-term, reliable gas cleanup and conditioning. The cost target will be met when tar and light hydrocarbons are sufficiently converted to additional syngas, technically validating the elimination of an additional unit operation to separately reform methane and other light hydrocarbons. This consolidated gas cleanup and conditioning concept is shown in the block flow diagram in Figure F-4.

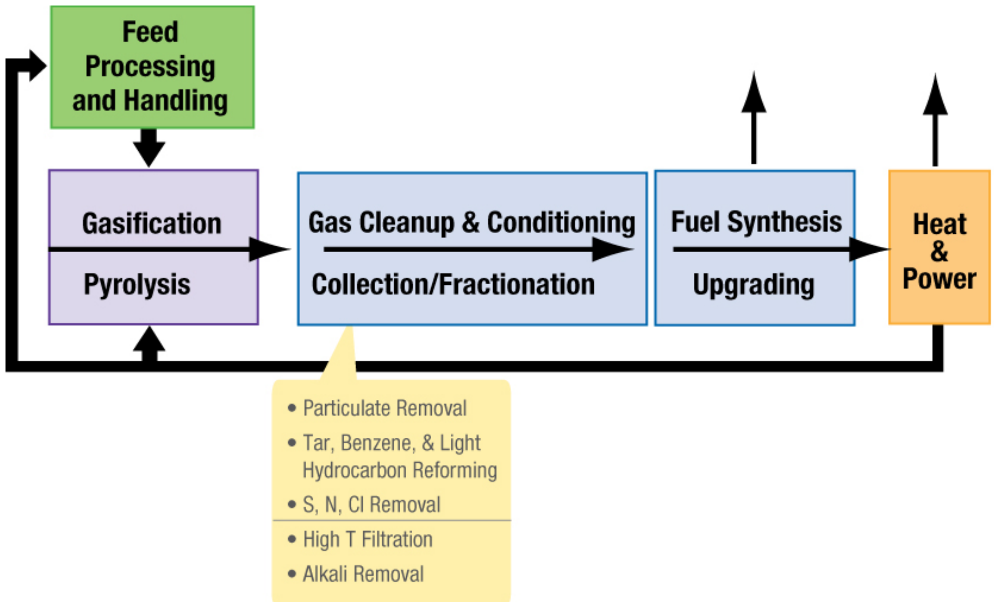


Figure F-4. Block Flow Process Diagram Showing Consolidated Gas Cleanup and Conditioning

Additional reforming catalyst development will provide incremental improvements in catalyst activity, lifetime, and resistance to impurities. Consolidated tar and light hydrocarbon reforming with nickel-based catalysts demonstrates the technical feasibility for this gas cleanup and conditioning strategy. Alternative catalyst formulations can be developed to optimize reforming catalyst activity and lifetime and expand functionality. Further process intensification is possible by designing catalysts with higher tolerances to sulfur and chlorine poisons. Further reductions in gas cleanup costs could be realized by lowering or eliminating the sulfur and chlorine removal cost prior to reforming. Optimizing the water gas shift activity of reforming catalysts could also reduce or eliminate the need for an additional downstream shift reactor.

R&D partnerships will focus on the development of materials, catalysts, manufacturing technologies, and combinatorial catalyst designs. Technical validation of tar and light hydrocarbon reforming is paramount to developing thermochemical technologies. Fuel synthesis and reforming catalyst activity and lifetimes can be optimized by including cost-effective, efficient means of mitigating sulfur-, chlorine-, and nitrogen-containing species in syngas. Alternative, dry reforming chemistry to mitigate tars and light hydrocarbons could improve process integration with a biochemical ethanol process by effectively using a high-volume, low-value waste stream from the fermentation process.

F.4.5 Advanced Catalysts and Process Improvements for Mixed Alcohol Synthesis

Improved mixed alcohol catalysts would increase the single-pass carbon monoxide conversion from 38.5% to 50%, and potentially higher, and improve the carbon monoxide selectivity to alcohols from 80% to 90%. Improved mixed alcohol catalysts with higher activity could require a lower operating pressure (1,000 psia compared with 2,000 psia), which could reduce process operating costs. The energy requirement for the improved

synthesis loop is therefore reduced because of the combination of lower syngas pressure for alcohol synthesis and less unconverted syngas to recompress and recycle. Overall, product yields could increase substantially by improving synthesis catalyst performance, thus simplifying the overall fuel synthesis process.
Alternative mixed alcohol synthesis reactors and catalysts should also be explored. Greatly improved temperature control of the exothermic synthesis reaction has been demonstrated for methanol synthesis in slurry-phase reactors. The suspension of catalysts in a heat-transfer fluid maintains the reaction temperature precisely, which results in higher selectivity to ethanol and improved yields. Slurry-phase reactors for mixed alcohol synthesis should be evaluated as part of future R&D. Optimizing catalyst performance in slurry-phase reactors should result in enhanced thermochemical ethanol synthesis processes. Other novel reactor designs, such as microchannel reactors, may also have the potential to improve thermochemical ethanol production.

Improvements in mixed alcohol synthesis catalysts could potentially increase alcohol yields and selectivity of ethanol production from clean syngas. Partnerships with catalyst manufactures and reactor design engineers are expected to achieve this goal. Techno-economic analyses and process design for other potential fuels (e.g., Fisher-Tropsch gasoline, Fisher-Tropsch diesel, and methanol) from syngas will also be investigated.

F.4.6 Process Sensors and Controls

Better monitoring sensors are needed for biomass feed systems to ensure reliable feed supplies to thermochemical processes. Thermochemical conversion of biomass also creates unique gas impurities, such as heteroatom tars and alkali, for which there are currently no adequate real-time, online sensors. Partnerships among national laboratories, universities, and instrumentation developers to establish concepts for monitoring these and other gas-phase species during system operation should be pursued. The development of such sensors and automated controlling systems is expected to improve the operability and reliability of biorefineries.

F.4.7 Thermochemical Platform Analysis

Techno-economic analysis and process modeling of the thermochemical conversion processes will determine the cost of biofuels production using currently available and developing technologies. This analysis is used to evaluate major process steps, highlight the most important technical barrier areas, and provide options for reducing biofuel production costs. Lifecycle assessments will be conducted along with techno-economic analysis to determine the sustainability of thermochemical pathways. Analysis results will be provided to decision makers.

F.4.8 Fundamental Gasification Studies

To maximize the efficiency of biomass conversion, future biorefineries will require optimized integration of biochemical and thermochemical conversion processes. R&D efforts are focused on establishing baseline information for gasification of residue streams generated by current and future biorefineries. This will enable the development of gasification technologies that are cleaner, more efficient, and more appropriate for a variety of feedstocks. Fundamental thermochemical conversion of biorefinery residues will be performed to determine how residue composition affects syngas composition and quality. Residues of interest include those that are out-of-spec and undesirable for the fermentation of corn stover, lignin-rich streams, and other in-process sugar biorefinery streams and materials such as corn fiber and distillers dry grain.

Other biomass feedstocks considered for integrated biorefineries include wheat straw, switchgrass, poplar, and forest and wood residues. Each of these streams has a different elemental composition. Of particular interest will be elements such as nitrogen, sulfur, and chlorine. They also have very different compositions in terms of carbohydrate-to-lignin ratios, which could influence tar formation. All of these features will affect the quality and value of the syngas as an intermediate for mixed alcohol production.

Alternative gasification technologies, such as pressurized oxygen-blown systems for dry feedstocks and wet gasification or hydrothermal processing for wet feedstocks, should also be evaluated. Pilot-scale data for these systems will provide input for techno-economic analyses that optimize process integration, heat integration, thermal efficiency, and overall process economics.

Appendix G: Advanced Conversion Technology R&D for Integrated Biorefineries

The technology advancements needed to achieve $1.07/gallon lignocellulosic ethanol are milestones on the path to energy independence. A well-defined R&D approach addresses the major technical barriers to cost reductions in biochemical and thermochemical conversion. However, achieving 30 x 30 will require continued efforts to reduce production costs by employing advanced, integrated biorefinery technologies beyond 2012. Projections for advanced biofuels estimate ethanol production costs ranging from $0.59/gallon to $0.91/gallon of gasoline equivalent by the 2030 timeframe, given a robust R&D program (Greene 2004, Ruth and Ibsen 2005).

Preliminary market analysis, based on results from the Biomass Transition Model, suggests that achieving the goal will require additional technology advancement and demonstration to drive down production costs and increase ethanol market penetration and consumer acceptance.

Future R&D efforts will focus on four areas to achieve the 30 x 30 goal:

- Advanced, large-tonnage feedstock supply systems
- Technology integration, economics of scale, and evolutionary process optimization
- Systems biology for biochemical processing improvement
- Selective thermal transformation for thermochemical processing improvement.

Taken independently, these areas of research will not result in technology improvements that will meet the 30 x 30 goal. Together, however, they will yield quantifiable process improvements that will guide future biorefinery technology development to meet and hopefully exceed the 30 x 30 goal.

G.1 Advanced, Large-Tonnage Feedstock Supply Systems

Advanced feedstock supply systems will be needed to collect the large tonnages of feedstocks required for large-scale biorefineries. By 2012, functional feedstocks supply systems will have been demonstrated, and feedstock R&D needs will shift to increasing the accessible biomass tonnage sufficient to produce 60 billion gallons of ethanol/year.

An efficient interface between producers and the commodity biomass systems will be varied, based on biomass resources and local practices. Primary research needs include storage, pre-processing, and transportation systems that are suited to the varied systems. Advanced feedstock supply systems will also rely heavily on the development of new transportation methods and technologies to take advantage of value-added pre-processing and merchandising of raw feedstock material. Advanced transportation systems will likely incorporate technologies that not only provide infrastructure and operational cost savings but also incorporate in-transit value-added processes.

G.2 Process Improvement and Optimization

Process improvement R&D and plant optimization are low risk-approaches for technology development beyond 2012. The construction and operation of demonstration-scale biorefineries will reveal unit operations that require optimization and identify opportunities for process integration to maximize energy efficiency and biomass use. The operating experience and engineering data accumulated from demonstration plants will be used in the design of larger-scale biorefineries to reduce production costs by leveraging economies of scale.

Three advanced, integrated biorefineries were identified as models for future R&D:

1. **Integrated biochemical-thermochemical biorefineries that use lignin for combined heat and power and fuel production**
   As plant scales increase, the volume of lignin-rich residues increases. At a certain point, these residues can be gasified to provide combined heat and power and converted to ethanol and mixed alcohols through fuel synthesis. Biorefinery ethanol yield will increase after the integration of thermochemical processing to convert lignin-rich residues to ethanol, as shown in Figure G-1.

   Better use of corn stover also results in higher yields. Integrating the gasifier/fuel synthesis steps raises yield 20% while supplying heat and power for all processes. The integrated biorefinery in Figure G-1 assumes 10,000 MT/day of biomass is processed and that the biorefinery capitalizes on all process improvements identified. Capital and operating costs associated with integrated biorefineries are partially offset by the economies of scale of the biochemical ethanol process and integration of the processes.

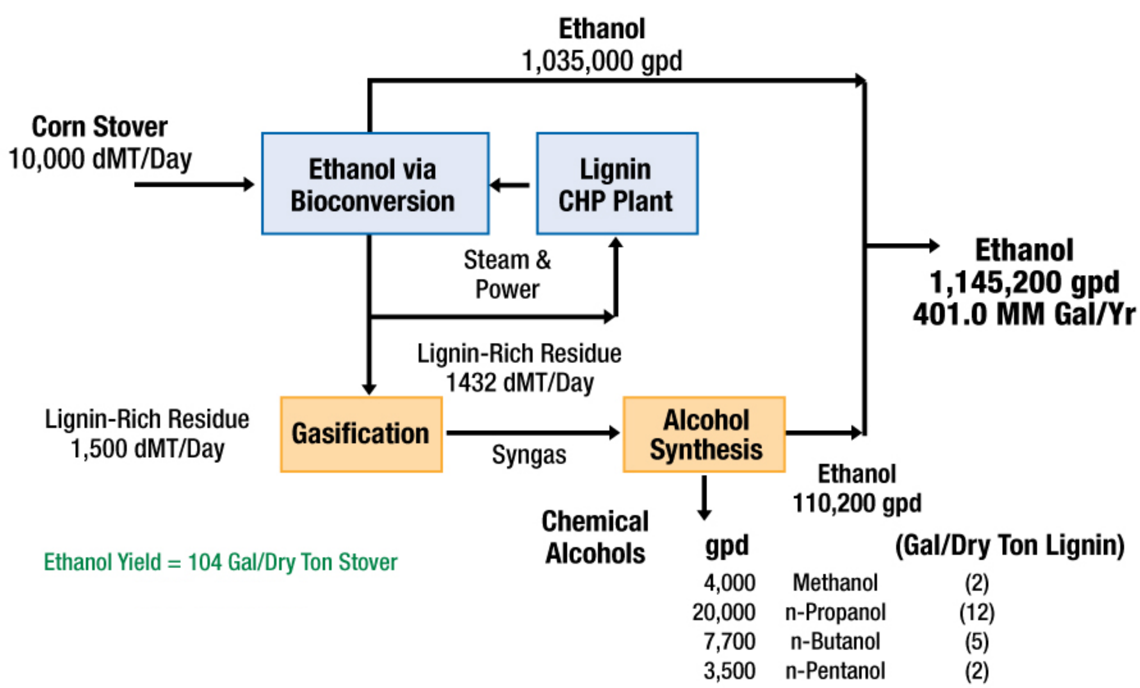


Figure G-1. Integrated Biochemical-Thermochemical Biorefinery Gasification Scenario with Excess Lignin Converted to Ethanol

2. **Integrated biochemical-thermochemical biorefineries that maximize lignin ethanol production**
   If the goal of advanced, integrated biorefineries is to maximize liquid fuel yields from lignocellulosic feedstocks, then an alternative, low-cost fossil fuel such as coal can be used to meet heat and power demands (Figure G-2). This scenario yields maximum lignocellulosic ethanol per ton of corn stover delivered to the plant gate by using all available lignin-rich residues from the biochemical conversion process in thermochemical gasification to produce ethanol.

   This scenario is a subset of the first scenario. The same process improvements and integration opportunities in the first scenario are accounted for here.

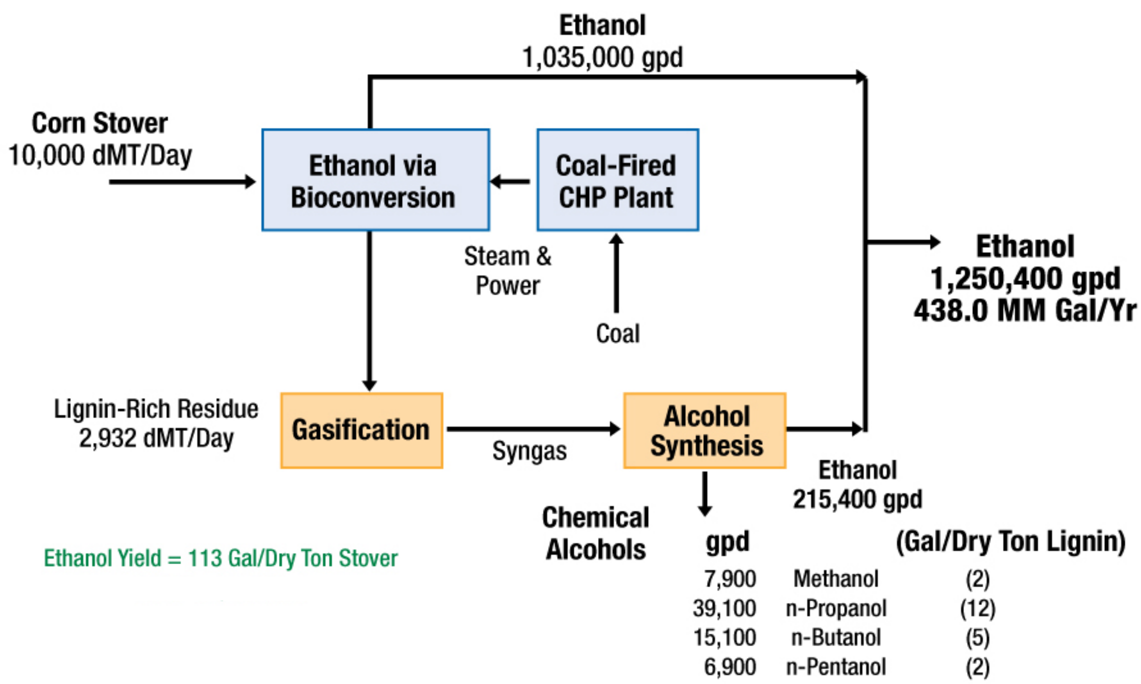


Figure G-2. Integrated Biochemical-Thermochemical Biorefinery Gasification Scenario Maximizing Ethanol Production

3. **Advanced, integrated biochemical-thermochemical biorefineries in the "E85" scenario**
   A scenario in which the thermochemical conversion technology is based on the conversion of lignin to gasoline- and diesel-range hydrocarbons is also considered. The process scenario shown in Figure G-3, in which the biomass is converted to ethanol biochemically and the excess lignin-rich residues are converted to gasoline, is dubbed the "E85" scenario because the approximate ethanol-to-gasoline ratio is 85%.

   The pyrolysis technology is based on the thermochemical conversion scenario that used the pyrolytic lignin fraction of bio-oils as a feedstock for a high-temperature, high-pressure catalytic hydrotreating process. The assumption in this scenario is that the lignin-rich residues can be transformed into a feedstock for the hydrotreating process and converted to gasoline with identical yields as the conversion of the pyro-lignin. As a first approximation, the lignin-rich residues are mixed with the diesel fuel from the thermochemical process to form a slurry that can be pumped into the hydrotreating process.

The impact of the diesel-range hydrocarbons on yields and conversion efficiencies in this step are unknown, and the actual conversion efficiency of the lignin-rich residues to gasoline have not been measured experimentally. This scenario clearly contains unproven assumptions; however, it demonstrates the potential process flexibility of advanced, integrated biorefineries to combine biochemical and thermochemical processes to maximize fuel production.

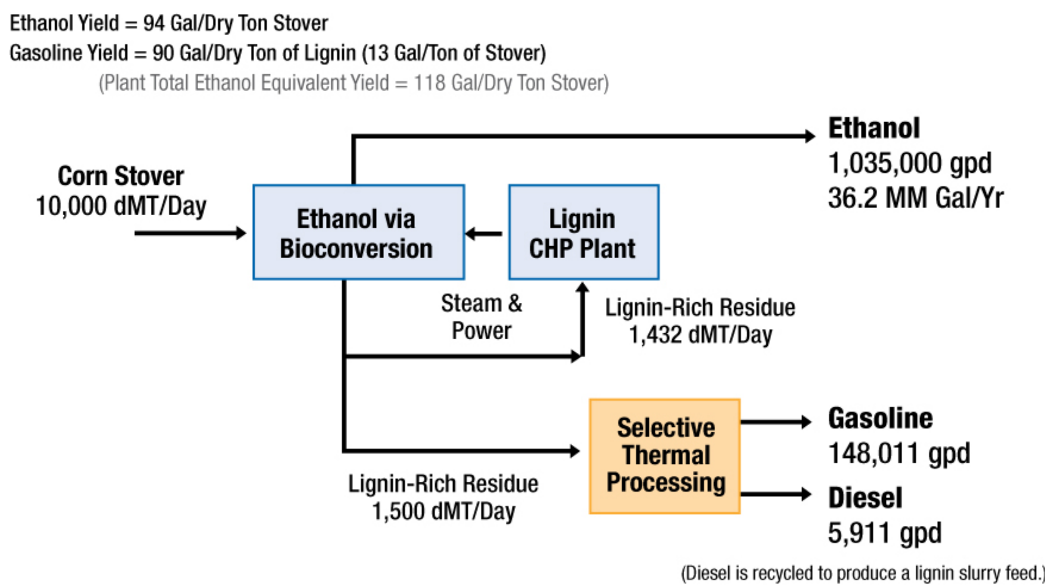


Figure G-3. Advanced, Integrated Biochemical-Thermochemical Biorefinery – "E85" Scenario

G.3 Advanced Biological Processing

To maximize ethanol potential, a base of new fundamental science must be engaged. To this end, research activities must be coordinated between EERE and the Office of Science. To achieve an advanced state of biofuels production, fundamental R&D in systems biology and thermal transformations and applied R&D are required.

G.3.1 Biological Processing: A Systems Biology Approach Using Translational Science

Translational science, a concept familiar to the biomedical industry, is an integrated approach to connecting basic research and industrial application. Regardless of the technical topic, fundamental science must be well integrated with applied objectives to ensure success.

Figure G-4 and Figure G-5 illustrate the advances in biorefinery processing from a systems biology perspective. Figure G-4 depicts the $1.07/gallon case for the biochemical conversion of biomass to ethanol; Figure G-5 depicts the advanced case. To enable this advancement, fundamental research in systems biology integrated with applied R&D in biomass conversion is needed.

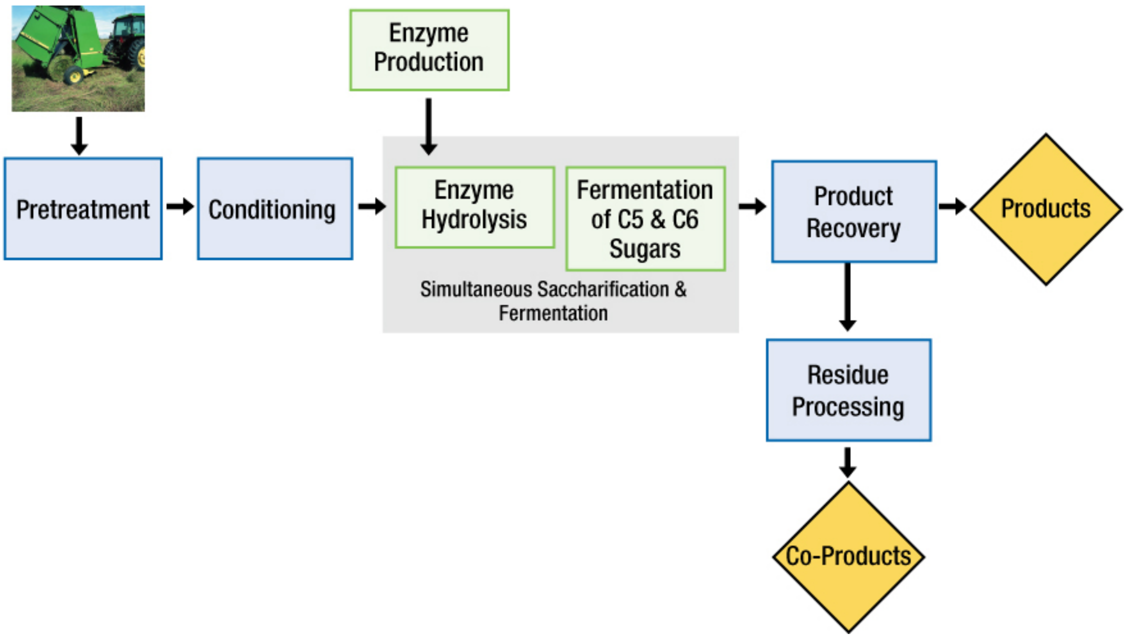


Figure G-4. Process Schematic of $1.07/gallon Ethanol Production

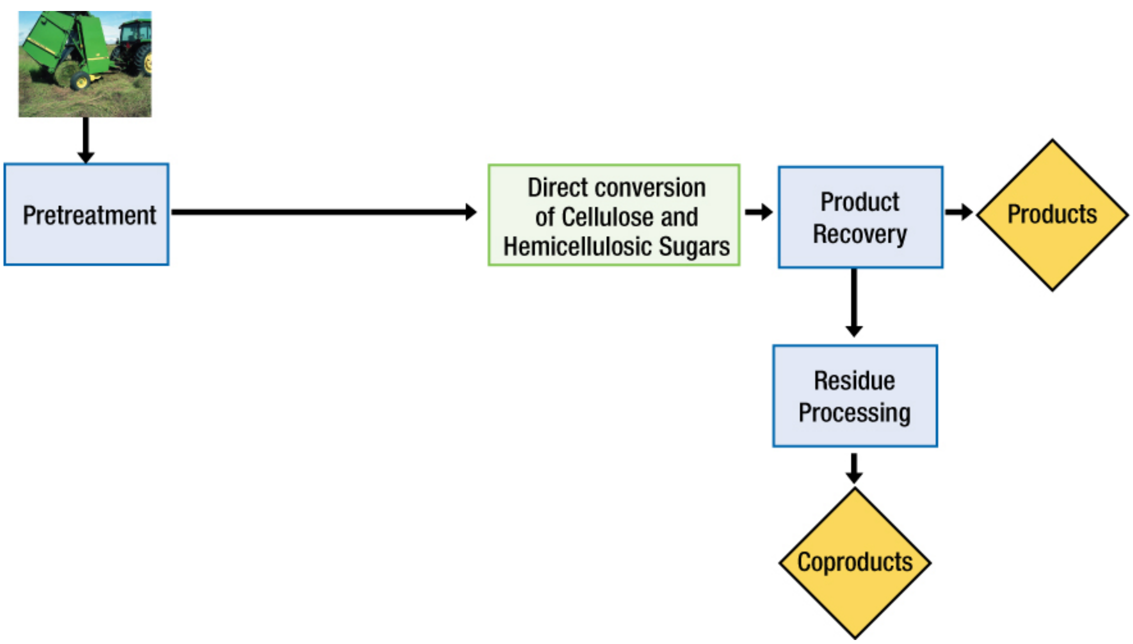


Figure G-5. Process Schematic of an Advanced State of Ethanol Production

The advanced state of technology depicted in Figure G-5 projects a capital cost savings from the $1.07/gallon case of approximately 50% per installed gallon (Wallace 2006). It projects a cost savings of 38% compared with the same-size plant using advanced technology. Process intensification brought about by incremental process improvements and breakthrough technologies will reduce the constraint of available capital and enable the large-scale deployment of biorefineries necessary to achieve the 30 x 30 goal.

In general, a full and detailed integration of science and engineering research will lead to the most efficient process development plan. In the case of biomass conversion, work in the fundamental area must be targeted to process improvements based on technical barriers. An integrated fundamental and applied research program in biochemical conversion must include advancements in the following three areas of biomass conversion:

- **Area 1: Energy plant engineering**
  The goal of plant engineering R&D is to maximize lignocellulose accumulation by energy crops per acre in an environmentally and economically sustainable way. Optimized energy crops for biorefinery use must minimally produce "useful" carbon in the form of polysaccharides that can be efficiently hydrolyzed to fermentable sugars. With directed R&D in plant engineering, energy plants may also produce byproducts important to the economic viability of the process. Such additional revenue-generating products may include animal feed supplements, chemicals, lipids and oils, and other industrial enzymes such as laccases, proteases, and amylases.

  The objectives of the R&D are to:

  - Address GTL strategies to maximize the biomass yield and agronomics of developing energy crops
  - Design and manipulate plant cell wall composition and structure to maximize yield of fermentable sugars.

  Plant engineering R&D needs to be directed to the following areas:

  - Expression of hydrolytic enzymes in the plant tissue
  - Regulation of lignin levels in plants
  - Increases in plant polysaccharide levels
  - Fundamental genomic research in potential dedicated bioenergy crops and trees.

  Genetically engineering plants to express cellulase enzymes has begun with the expression of *Acidothermus* E1 endoglucanse in the model plant species *Arabidopsis*, which was expressed to 2%–5% of the soluble protein (Stricklen 2006). In addition, the lignin-modifying enzyme laccase has been successfully expressed in maize apoplast by industry (Hood 2004).

The development of plants with reduced or modified lignin has long been a goal for improving biomass feedstocks because of the inhibitory effects of lignin degradation products on the bioconversion process. Also, reduced lignin may positively influence polysaccharide levels. For example, transgenic aspen produced with reduced lignin showed a 15% increase in cellulose with no negative effects (Dean 2005). Furthermore, tobacco showed an increased yield upon insertion of a flowering locus from *Arabidopsis* (Rose and Bennett 1999), apparently because delayed flowering permitted longer vegetative growth.

A longer-term approach for plant feedstock improvement uses the latest biological tools with the sequencing and annotation of the Populus genome. Access to the genetic portfolio of this fast-growing tree species will help extend the basic work with the model dicot plant species, *Arabidopsis*, and permit the comparative analysis of selected genes and pathways for other plant crop genomes such as corn, soybean, and rice.

- **Area 2: Plant cell wall deconstruction**
  Advances in GTL and biochemistry tools can improve plant productivity and chemical composition. Novel and more efficient technologies will also facilitate analysis of plant cell wall compositions for breeding and basic research. In many cases, methods capable of higher throughput and increased precision are required for improved GTL-based research.

  The objectives of plant wall deconstruction R&D are to:

  - Develop a more detailed understanding of plant cell wall structure, including elucidating glycosyl hydrolase structure/function
  - Develop improved engineered enzymes for advanced biochemical conversion technologies.

  Recent cellulase cost reduction advances achieved by DOE/OBP-funded research have provided, for the first time, a real opportunity for enzymatic saccharification of lignocellulose processes. Although a 30-fold reduction in enzyme cost has been achieved by Genencor International and Novozymes Biotech, further cost reductions are required to achieve an economic and robust biorefinery industry. For example, the costs of amylases for starch to ethanol processes are about $0.01–$0.02/gallon of ethanol produced, and the most optimistic estimates for the cost of cellulase preparations is now about 10-fold more.

  More than 95 families of polysaccharide-degrading enzymes have been identified. However, only seven harbor cellulases, and only 12 are linked to hemicellulose disassembly (Boeckmann et al 2003, Coutinho and Henrissat 1999). Developing an understanding of the structure/function controls of these protein machines, their diversity in nature, and the changes they promote on the surfaces of plant cell walls is critical to the attainment of the 30 x 30 goal. Research needs to address the synthesis and structure of the plant cell wall with a new outlook toward disassembly.

Research in this field has traditionally looked at cell wall synthesis from a botanical perspective (Persson et al. 2005; Anderson-Gunneras et al. 2006). New research should target ways to modify the cell wall assembly apparatus to produce plants that are more easily digested and yield an optimal mixture of fermentable sugars. To meet these objectives, an understanding of cell wall engineering and cellulase action is needed.

There are challenges associated with acquiring a new understanding of the substrate at the molecular level and the mechanisms of action of the glycosyl hydrolases that act on these surfaces. Plant biomass has evolved superb mechanisms for resisting assault on its structural sugars from the microbial and animal kingdoms (Himmel, Baker, and Overend 1994; Himmel, Baker, and Saddler 2001).

- **Area 3: Biomass sugars conversion**
  The lack of a robust fermentation organism that can convert all of the sugars derived from lignocellulosic biomass to ethanol at sufficient rates, yields, and titers is a barrier that must be overcome if the $1.07/gallon target is to be achieved (Himmel et al. 1997). Although most of the strains in the public sector perform reasonably well at low sugar concentrations (solids loadings less than 10%–5%), the market target calls for the use of 20% (or more) solids with the conversion of the majority of sugars to ethanol (Toon et al. 1997; Bothast et al. 1994). Clearly, under these conditions, the available strains cannot be used at a commercial scale. Therefore, the development of robust, industrial fermentation strains will require substantial knowledge about the factors that limit efficient sugar bioconversion. The collective knowledge of strain improvement will be critical to overcoming the technical barriers that limit current strain performance.

  The goal of this R&D is to target advanced conversion technologies of sugars released during biomass deconstruction to liquid fuels and products, wherein consolidated bio-processing is achieved.

  To achieve strain improvement goals, new and novel research must be conducted in aspects of cell morphology and physiology. For example, information about the structure and function of sugar transport enzymes is critical to improving the ability of strains to efficiently use all biomass-derived sugars. A new understanding of cell membrane function is also needed to improve the cells resistant to process-produced toxic substances. Finally, a deeper understanding of the gene- and protein-level metabolic controls of energy pathways in ethanologenic strains is critical. Special attention must also be given to metabolic pathway engineering and consolidation approaches to reducing cost in the long term. For example, the production of new generations of microbial strains able to ferment biomass sugars at high concentrations directly from pretreated biomass, with no exogenous hydrolytic enzymes added, should be pursued (Himmel et al. 1997).

  Advanced scenarios have been proposed to combine key process steps and thus reduce overall process complexity and cost. A reduction of process steps can be accomplished biologically by engineering a single micro-organism to perform the roles now associated with three or four strains. Although this goal is clearly longer-term, R&D

has been proposed for investigation. One notable example is the consolidated biomass processing technology proposed by Zhang and Lynd (2005) for the Clostridium thermocellum case. Zhang and Lynd believe these benefits exceed the bioenergetic cost of cellulase synthesis, which supports the feasibility of anaerobic processing of cellulosic biomass without added saccharolytic enzymes.

Another option for consolidated biomass processing is to enable yeast, already ethanologenic, to produce cellulases (VanRensburg, Zyl, and Pretorius 1998). In this case, expression of some active and effective cellulases from yeast has proved challenging (Godbole et al. 1999); however, endoglucanses and beta-glucosidases appear more amenable to yeast processing (VanRooyen et al. 2003).

Analysis bridges all research functions of the program. Analysis to support the three areas of R&D must include advancements in process application knowledge at two levels. The first will address key process-related engineering research that converts new understanding from fundamental research to the biorefinery context. The second will use process-related engineering information to make recommendations to industry about the selection of process parameters, equipment, and operating conditions.

- **Engineering research**
  This work targets the interface between fundamental science and process-scale integration engineering. It carries elements of both science and engineering research for that reason. This work will bring an engineering-level understanding to process unit operations by using computational modeling and experimental methods. The objective will be to acquire new understanding in broad-based aspects of applied process engineering research.

- **Process integration and modeling**
  This work addresses the barrier of process integration and will focus initially on integrating enzymatic hydrolysis process technology based on dilute acid pretreatment that incorporates advanced, lower-cost cellulase enzymes being developed. These activities will also include the continued development of rapid analysis techniques to generate timely mass balance data for application at the process scale. Analysis of process options will also be performed under this effort.

G.3.2 Thermochemical Technologies for 30 x 30 and Beyond

Achieving the near-term ethanol cost target of $1.07/gallon via biomass gasification/mixed alcohol synthesis will require improvements in catalytic tar and light hydrocarbon reforming to increase conversion efficiencies and reduce the capital costs of syngas cleanup and conditioning. This is the first step in an attempt to define barrier areas and unit operations that can be improved, combined, or eliminated to minimize capital and operating costs by intensifying thermochemical conversion processes.

Thermochemical conversion R&D from 2010 to 2030 will include two complementary approaches:

- Engineering approach: Process improvement and optimization
- Scientific approach: Advanced thermal processing.

G.3.2.1 Process Improvement and Optimization

The objective of this R&D path is to improve yields and efficiencies and maximize process integration opportunities in existing thermochemical processes.

Advances in catalysis and mixed alcohol synthesis will produce cost reductions. For example, improved mixed alcohol catalysts can increase the single-pass carbon monoxide conversion from 38.5% to 50% and improve carbon monoxide selectivity to alcohols from 80% to 90%. Improved mixed alcohol catalysts with higher activity could require a lower operating pressure—1,000 psia compared with 2,000 psia. The energy requirement for the improved synthesis loop is therefore reduced because of the combination of lower syngas pressure for alcohol synthesis and less unconverted syngas to recompress and recycle. Overall, the product yield increases by 12 gallons/dry ton of biomass. Combined, these improvements contribute to a reduction in the overall capital cost as well as operating costs.

Additional technical R&D includes improvements to the thermochemical conversion process to move the technology toward catalytic gasification to increase carbon conversion efficiencies to syngas and decrease tar formation. Within the gasifier, this design converts 50% of the methane produced during biomass gasification to carbon monoxide and hydrogen, thus reducing the methane in the raw syngas. The throughput of the gasifier also increases by 25%.

The block flow diagram in Figure G-6 illustrates the technical barriers that must be addressed to advance thermochemical conversion technology.

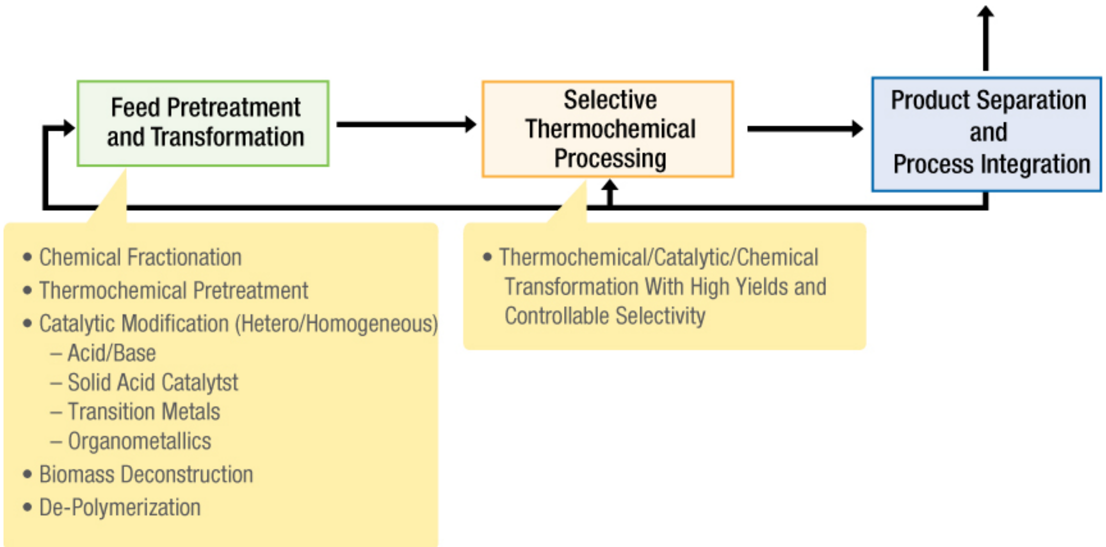


Figure G-6. Selective Thermochemical Processing

Future R&D efforts will focus more on the front end of thermochemical processes as the downstream unit operations are optimized. To this point, biomass feedstocks will be prepared for introduction into a specific thermochemical conversion process 9.(gasification or pyrolysis), and the output of the conversion process will be conditioned and optimized for subsequent fuel production.

There is also an opportunity to tailor the feedstock for thermal conversion to eliminate downstream intermediate conditioning and conversion. Feedstock processing and handling then involves not only size reduction and drying but also deconstruction to fractionate biomass into components with compositions most suitable for a specific conversion technology. This is analogous to the separation of crude oil into individual components at the front end of a petroleum refinery. With tighter limits on the composition of fractionated biomass materials, it seems plausible that selective thermal transformation of specific fractions could be developed for high-yield biofuels production with high selectivity. These selective thermal transformations effectively combine heat, catalysts, and chemical reagents to optimize the conversion of biomass to fuels. Advanced feedstock processing acts as the link between the engineering and scientific approaches defining thermochemical conversion R&D.

G.3.2.2 Advanced Thermal Processing

Biochemical processes for the conversion of biomass into sugars produce a wet, lignin-rich residue that contains unconverted carbohydrates, proteinaceous material from the enzymes and fermentative organisms used, and ash. Conversion of the lignin in this residue to higher-value products is challenging because of the high moisture content and presence of the other components.

Alternative strategies for lignin use need to be evaluated to make future biorefinery concepts technically and economically competitive. These strategies include gasification, pyrolysis, solvation, hydrotreatment, and hydrothermal treatment. The integration of lignin thermochemical conversion processes into biorefineries will require analysis and experimental validation to identify the most promising, highest-value options.

Developing robust, economic, and selective thermal transformation processes will leverage the R&D successes of both biomass gasification and pyrolysis. Establishing a rigorous research program to investigate fundamental biomass thermochemical conversion will help erase the lines between gasification and pyrolysis as separate technology options.

- **Area 1: Catalytic gasification and pyrolysis**
  Catalytic process improvements must be cost-effective to be commercially viable. Since the beginnings of coal gasification, catalysts have been sought to improve carbon conversion to products and increase gasification rates while minimizing temperature to increase process efficiency. Alkali metals have long demonstrated catalytic activity in steam gasification of solid fuels, and metal-based catalysts—particularly nickel-based materials—are active and effective for hydrocarbon reforming.

  R&D must investigate and identify active catalytic agents (e.g., potassium, calcium, phosphorous, nickel, sulfur trioxide, manganese, magnesium, and titanium) and determine how they can be exploited for technical and economic application in biomass gasification systems. Previous efforts to apply catalysis to biomass gasification through techniques for coal gasification have been, in general, unsuccessful. A targeted approach to understanding the effect of primary catalysts on gasification chemistry is required to optimize syngas compositions and minimize the effect of impurities (e.g., tars, sulfur, nitrogen, chlorine, and potassium) on downstream cleanup and conditioning unit operations. Ultimately, the successful implementation of gasification catalysts could lead to process intensification by eliminating the need for certain downstream cleanup and conditioning steps.

  Depending on the feedstock, these gasification catalysts may already be inherently part of the mineral matter of the solid fuel. This is the case for low-rank coals such as lignites and many biomass fuels. Many woody biomass fuels contain high fractions of calcium in ash, but the overall ash content is usually quite low (~1%), so the "catalyst" concentration is also low. Agricultural residues such as rice and wheat straws, alfalfa stems, and corn stover have relatively high ash content with high concentrations of potassium that can lead to higher "catalyst" concentrations.

- **Area 2: Lignin utilization**
  Lignin is present (at 15–30 wt%) in all lignocellulosic biomass. It is the component with the highest energy content (9,000–11,000 Btu/lb versus 7,300–7,500 for cellulose). Any process for making products from the carbohydrates in lignocellulosic biomass will have lignin-rich residues as a byproduct. Integration and use of lignin residues will be key for the commercial viability of lignocellulosic biorefineries and to maximize biomass utilization for fuel production.

  The phenolic nature of lignin makes it chemically different from all other renewables components. This makes it a potential source of products for the chemicals industry.

Although lignin is presently a low-value and complex biomass component, there is potential for new technology development to increase the value of this residue stream and significantly enhance the competitiveness of integrated biorefineries. The chemical and physical nature of lignin residues means that some fraction of the lignin will likely be resistant to conversion into higher-value products via traditional biochemical processing. Lignin pyrolysis is an alternative that could yield an additional, higher-value option for the production of aromatic fuel components and chemicals.

Advanced thermochemical conversion of lignin, such as integrated gasification combined-cycle systems, offers the possibility of increasing the efficiency of lignin use and providing excess power for additional revenue. Gas turbine systems offer electrical conversion efficiencies approximately double those of steam-cycle processes, and developing fuels cells are projected to be nearly three times as efficient.

- **Area 3: Selective thermal transformation of fractionated biomass**
  A range of alternative conversion options are possible through the fractionation of biomass into specific components. A narrower, uniform-composition biomass fraction enables thermochemical conversion options with high yields and selectivities. These selective thermal transformations combine heat, catalysts, and chemical reagents to optimize the conversion of biomass to fuels. Developing robust, economic, and selective thermal transformation processes will leverage the R&D successes of both biomass gasification and pyrolysis—and integrate the biomass pretreatment processes being developed for lignocellulosic ethanol production—into a single, consolidated biomass conversion process to meet or exceed long-range biofuel cost targets.

Appendix H: Life Cycle Environmental Analysis of Biofuels: GREET and VISION (vehicle needs) Simulation Results

H.1 Life-Cycle Analysis of Bioethanol

H.1.1 Bioethanol Production Cases for Life Cycle Analysis

This study examined three biofuel production options: an advanced biochemical ethanol production process, a thermochemical gasification process to produce mixed alcohols, and an advanced biorefinery process that integrates biochemical and thermochemical processes. These processes—all of which co-produce heat and electricity—were designed and simulated by NREL and Dartmouth College-Princeton University. For the project, Argonne National Laboratory conducted a mobility chains ("well to wheels," or WTW) analysis using the GREET model (Wu, Wu, and Wang 2005).

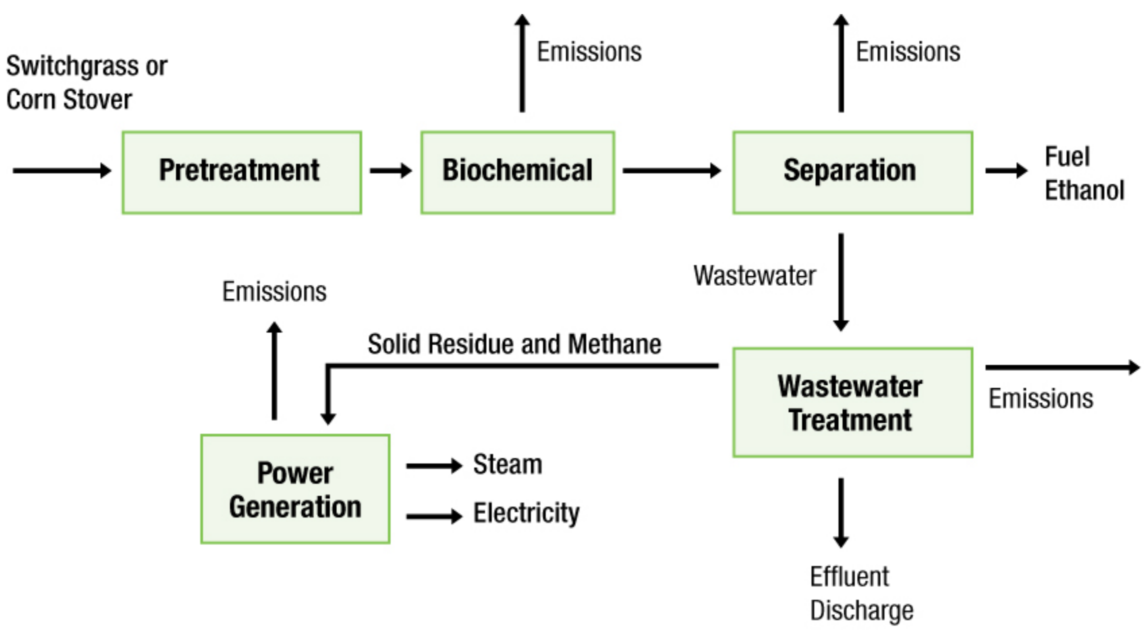
The mixed-alcohol thermochemical process and the biorefinery are in the early stages of quantification, and key parameters of the life cycle analysis may be subject to uncertainties. However, the analysis provides an indication of the potential energy and emission benefits of these processes relative to those offered by the biochemical ethanol production process. All three processes are being pursued by government and industry. The comparison of energy and emission benefits provides information to help researchers and decision makers evaluate the merits of biofuel production pathways.

Four feedstocks were considered for bioethanol production: corn, corn stover, switchgrass, and forest residues. To take into account process and technology advances over time, the energy and environmental effects of cellulosic ethanol were evaluated for the near term (2012) and the long term (2020–2030). To compare ethanol with gasoline, the analysis included gasoline production from conventional crude in 2012 and from a mix of conventional crude and oil sands in 2030. Thus, 10 cases were analyzed:

1. Conventional crude to gasoline in 2012
2. Corn to ethanol through conventional corn ethanol technology in 2012
3. Switchgrass to ethanol through biochemical conversion in 2012
4. Corn stover to ethanol through biochemical conversion in 2012
5. Forest residues to mixed alcohols through thermochemical (gasification) conversion in 2012
6. Conventional crude and oil sands to gasoline in 2030
7. Corn to ethanol through conventional corn ethanol technology in 2030
8. Switchgrass to ethanol through a biorefinery with consolidated bioprocessing and gasification turbine combined cycle (GTCC) in 2030
9. Corn stover to ethanol through a biorefinery with consolidated bioprocessing and GTCC in 2030

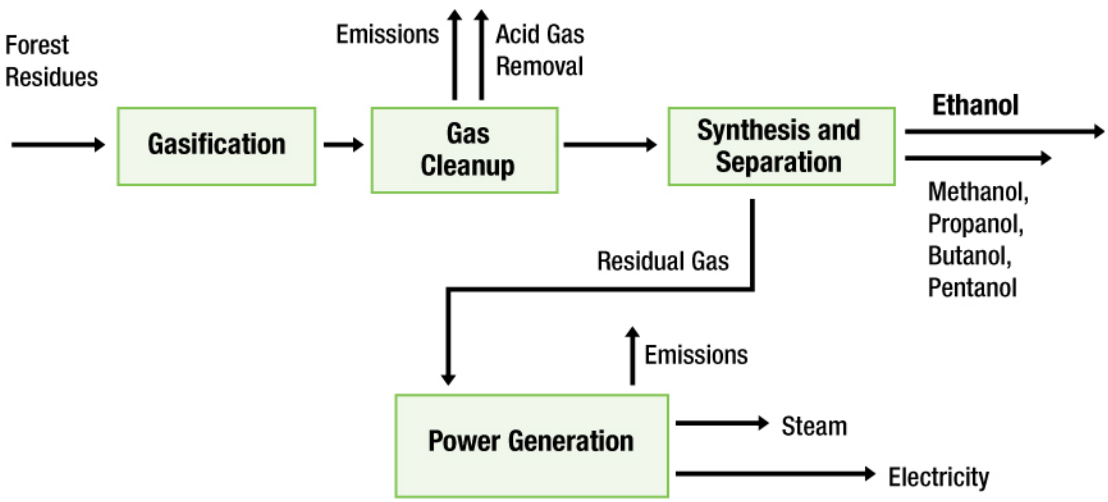
10. Forest residues to mixed alcohols through the biochemical-thermochemical biorefinery in 2030.

Figures H-1 through H-4 are flow diagrams for the cellulosic ethanol production scenarios. All cellulosic ethanol cases were based on Aspen Plus simulations. Of the 10 cases, the simulations for cases 1, 2, 6, and 7 (crude oil to gasoline and corn to ethanol in 2012 and 2030) relied on data collected at Argonne during its life cycle analysis using the GREET model (Wang, Wu, and Elgowainy 2005; Brinkman et al. 2005). Cases 3 and 4 (biochemical process with switchgrass and corn stover in 2012) are for a biochemical process that was simulated by NREL for a 2,000-dry-ton/day ethanol plant (see Figure H-1) (Jechura 2006b). Case 5 is a 2,000-dry-ton/day ethanol plant with thermochemical gasification (see Figure H-2) (Jechura 2006b). Cases 8 and 9 are the consolidated bioprocessing-GTCC process simulated by Dartmouth College and Princeton University for a 5,000-dry-ton/day cellulosic biomass feedstock biorefinery (see Figure H-4) (Laser and Jin 2004). Case 10 is a 2,000-dry-ton/day biorefinery with the biochemical and thermochemical process simulated by NREL (see Figure H-3) (Jechura 2006b).



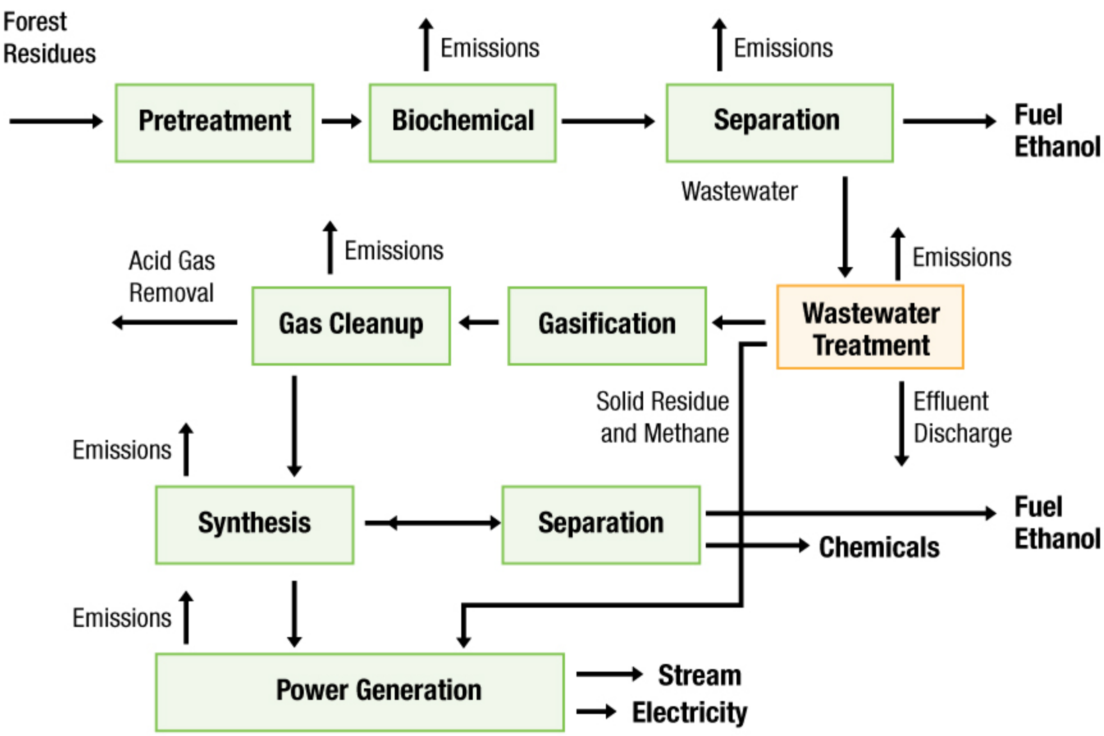
(Jechura 2006b)

Figure H-1. Simplified Process Flow Diagram of Biochemical Conversion of Switchgrass and Corn Stover to Ethanol with Steam and Electricity Cogeneration



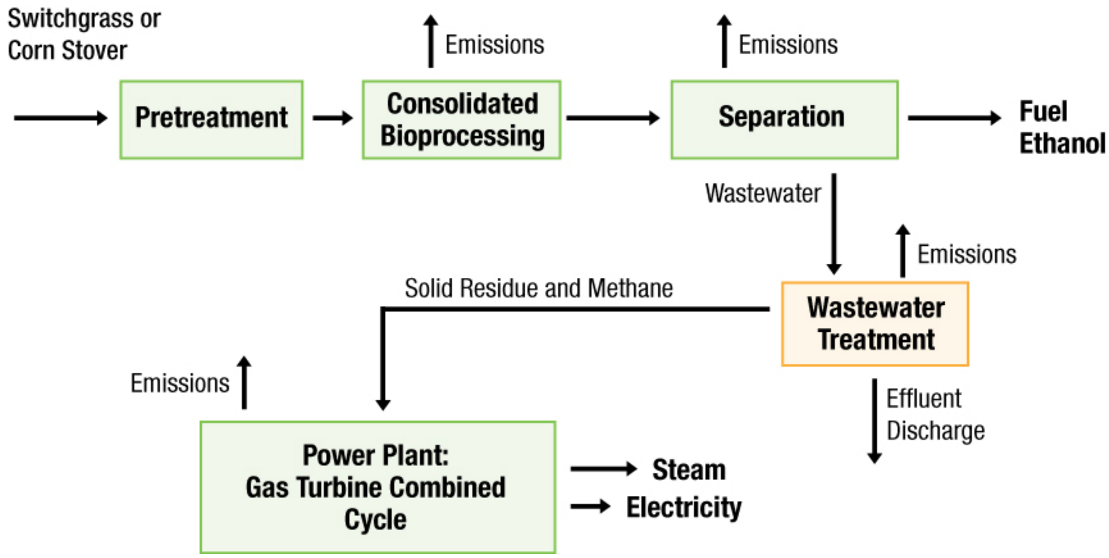
(Jechura 2006b)

Figure H-2. Simplified Process Flow Diagram of Thermochemical Conversion of Forest Residues to Ethanol and Other Alcohols with Steam and Electricity Co-generation



(Jechura 2006b)

Figure H-3. Simplified Process Flow Diagram of a Biorefinery that Co-produces Ethanol, Steam, Electricity, and Other Chemicals from Forest Residues



(Laser and Jin 2004)

Figure H-4. Simplified Process Flow Diagram of a Biorefinery that Co-produces Ethanol, Steam, and Electricity from GTCC

Ethanol production process data from Aspen Plus simulations that serve as GREET inputs are listed in Table H-1. Co-product credit partitioning is discussed in Section G.1.3.3.

H.1.2 GREET Model

Since 1995, with support primarily from EERE, Argonne has been developing the GREET model. Argonne released its first version, GREET 1.0, in June 1996.

GREET is a Microsoft® Excel™-based multidimensional spreadsheet model that addresses the WTW analytical challenges associated with alternative fuels and vehicle technologies. The latest version, GREET 1.7, can analyze more than 90 transportation fuel pathways and 75 vehicle/fuel systems (Wang, Wu, and Elgowainy 2005). A licensed software product is available free of charge to the public, GREET has more than 3,000 registered users worldwide. Users include government agencies, automotive companies, energy companies, universities and research institutions, and non-governmental organizations.

Table H-1. Key Ethanol Production Process Data Used to Determine GREET Inputs

Case[a]	Ethanol	n-Propanol	n-Butanol	n-Pentanol	Methanol	Electricity Export (KWh/dt Feed)
	Fuel and Chemical Yield (Gal/dt)					
2012						
Case 3: Switchgrass to Ethanol Through Biochemical Conversion	75.97	NA[b]	NA	NA	NA	362.4
Case 4: Corn Stover to Ethanol Through Biochemical Conversion	89.84	NA	NA	NA	NA	215.5
Case 5: Forest Residues to Mixed Alcohols Through Thermochemical Conversion	66.65	12.11	4.67	2.13	2.45	-53.8[c]
2030						
Case 8: Switchgrass to Ethanol Through Biochemical Conversion and GTCC	105	NA	NA	NA	NA	604.3
Case 9: Corn Stover to Ethanol Through Biochemical Conversion and GTCC	105	NA	NA	NA	NA	604.3
Case 10: Forest Residues to Mixed Alcohols Through Biochemical/Thermo-chemical Biorefinery	103.92	1.81	0.70	0.32	0.37	765.6

[a] Process data for cases 1, 2, 6, and 7 are default GREET values, so these cases are not included in the table.
[b] NA = not applicable.
[c] A negative value indicates electricity import from the grid is required.

For a given vehicle and fuel system, GREET separately calculates:

- Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal), and petroleum
- Emissions of carbon dioxide-equivalent GHGs (primarily carbon dioxide, methane, and nitrous oxide)
- Emissions of five criteria pollutants:
    - VOCs
    - Carbon monoxide
    - Nitrogen oxide
    - Particulate matter of diameter smaller than 10 microns (PM_{10})
    - Sulfur oxides.

The criteria pollutant emissions are further separated into total and urban emissions.

Although this work covers the full fuel cycle (from cellulosic feedstocks production to fuel processing to vehicle operations), it does not include energy or emissions associated with farm equipment and vehicle manufacturing, capital equipment and infrastructure in manufacturing facilities, and construction of transportation infrastructures. For a fair comparison, if energy use and emissions from these activities are to be included for biofuels, energy use and emissions from the construction of oil field rigs, ocean tankers, pipelines, and petroleum refineries should be included in gasoline life cycle analysis. Overall, the completed studies that include these infrastructure-related activities show that their contribution to total life cycle energy use and emissions is relatively small per unit of fuel.

H.1.3 Methodology and Assumptions

H.1.3.1 Modeling Boundary

Fuel pathways simulated in this study are divided into five stages: biomass farming; biomass feedstock transportation; fuel production, fuel product transportation, distribution, and storage; and fuel use during vehicle operation.

The GREET modeling boundary for this study is depicted in Figure H-5. As the figure shows, bioethanol life cycle analysis begins with the manufacture of fertilizer. Cellulosic biomass is transported via trucks to the fuel production facility, where it undergoes biochemical or thermochemical processing for fuel production. The demand for heat and power (through steam and electricity) from the biochemical and thermochemical plant is met by employing a biomass fluidized bed combustion boiler, GTCC, or importing electricity and natural gas. Fuel products are then transported to refueling stations via rails, barges, and trucks. Bioethanol is used as E85 (a mixture of 85% ethanol and 15% gasoline by volume) to fuel flexible-fuel vehicles (FFVs) or in low-level ethanol blends such as E10 (10% ethanol and 90% gasoline by volume) in gasoline vehicles.

Gasoline life cycle analysis, on the other hand, begins with crude oil recovery in oil fields and ends with gasoline combustion in gasoline-powered vehicles.

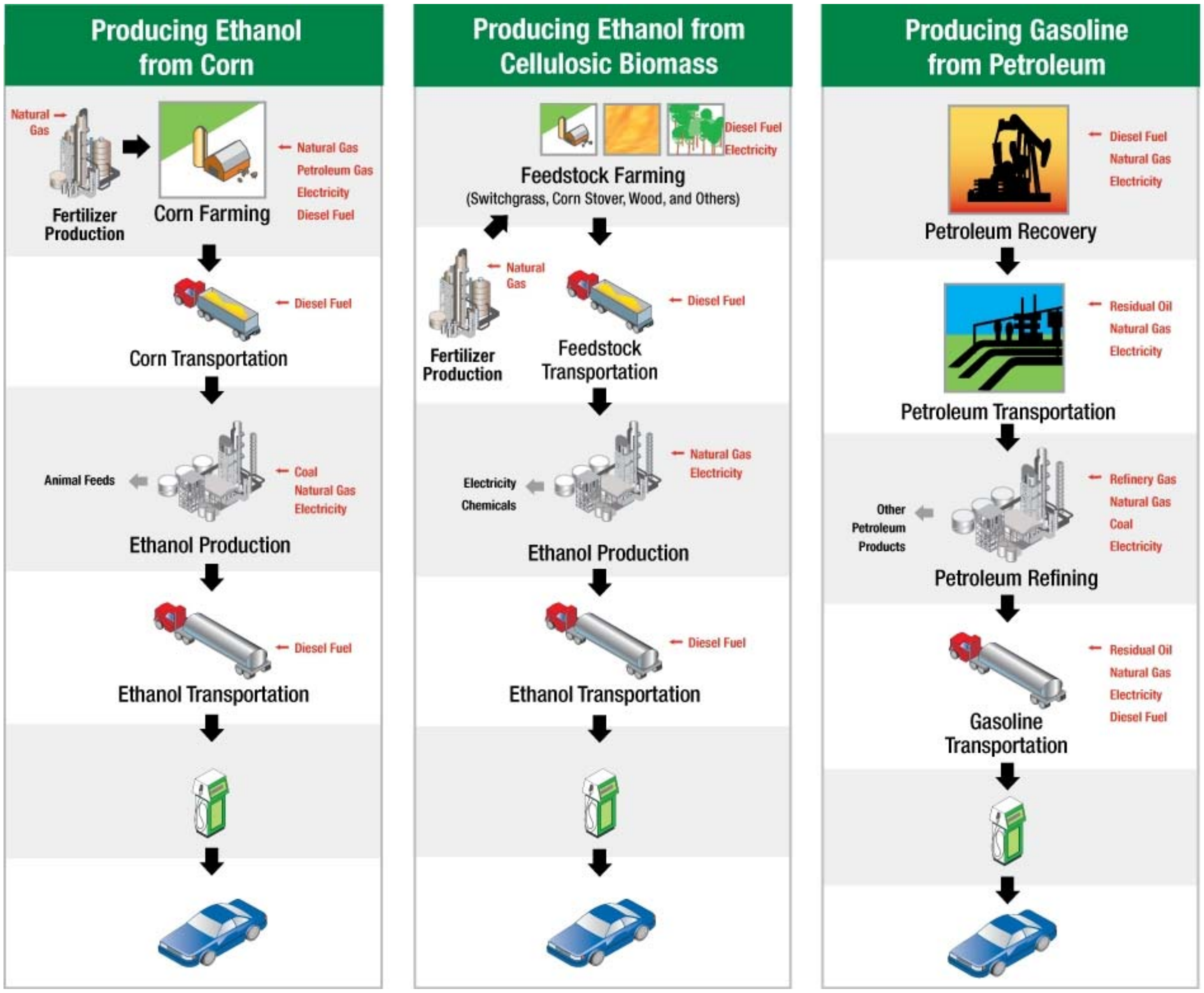


Figure H-5. GREET WTW Modeling Boundary

H.1.3.2 Data Sources and Assumptions

GREET modeling input parameters are collected from literature, published reports, field expertise, and ASPEN simulations (as described in Section H.1.1). Table H-2 lists major processes and operations and their data sources. Detailed GREET input parameters and assumptions for the cellulosic biomass feedstocks are provided in Tables H-3 through H-5.

For ethanol use in vehicles, both E10 and E85 were assumed. E85 was assumed to achieve the same fuel economy per gallon of gasoline equivalent in FFVs as gasoline in gasoline-powered vehicles (Table H-6). The crude oil source for gasoline production in 2030 includes oil sands as well as conventional crude.

Fertilizer is a major source of the energy use and emissions associated with corn farming operations. There is a baseline value for fertilizer use when corn grain is the only product harvested. Additional fertilizer will be needed when corn stover, an agriculture residue, is collected to produce ethanol because corn stover (with an assumed mass-to-grain ratio of about 1:1) has traditionally been left in corn fields as a carbon and nutrient source. In current practice, almost 100% of stover is left in the field. The removal of corn stover will therefore require additional fertilizer (e.g., nitrogen, phosphorus, and potassium) to supplement its nutrient value. The additional demand for fertilizer is included in the two corn stover cases and is accounted for in the corn stover-based pathways.

The issue of energy and emission partitioning between corn and corn stover arises in the estimation of baseline fertilizer use. In previous corn ethanol life cycle analyses, as in this study, all of the baseline fertilizer use is allocated to corn grain. However, it is conceivable that some portion of baseline fertilizer use could be allocated to corn stover if it becomes a vital feedstock for ethanol production. Consequently, the energy and emission benefits of corn stover to ethanol should be examined when stover is no longer an agricultural residue but a commercial feedstock. In this analysis, corn stover is treated as an agricultural residue, and no baseline fertilizer use was allocated to corn stover.

Table H-2. Major Processes and Their Data Sources

Process	Data Sources
Corn Stover Collection	Sheehan et al. (2002), Spatari, Zhang, and Maclean (2005), Kim and Dale (2005)
Switchgrass and Corn Stover Transportation to Ethanol Plant	Sheehan et al. (2002), Hess and Perlack (2006)
Forest Residue Collection and transportation	Hess and Kelley (2006)
Corn to Ethanol Conversion	GREET default values with incremental technology advancement to 2030
Biochemical Conversion to Ethanol (2012)	Jechura (2006b)
Thermochemical/Gasification Conversion to Ethanol (2012)	Jechura (2006b)
Biorefinery Consolidated Bioprocessing to Ethanol with GTCC (2030)	Dartmouth College and Princeton University, RBAEF (Laser and Jin 2004)
Biorefinery Biochemical-Thermochemical Conversion to Ethanol (2030)	Jechura (2006b)
Ethanol Transportation	GREET default values
Vehicle Operation	GREET default values

Table H-3. Detailed Assumptions: Switchgrass to Ethanol

	Assumptions
Farming Operation	
Switchgrass Yield	Estimated from national average yield increase of 0.165 ton/acre/year through breeding from the base-year yield of 4.96 ton/acre/year (2004) based on Greene (2004)
Switchgrass Transportation Distance From Farm to Ethanol Plant	Ethanol plant surrounded by farmland with 2.2% acreage coverage for switchgrass farming in 2012 and 3.8% in 2030, based on Dartmouth College and Princeton University data (Laser and Jin 2004) 50-mile one-way distance by heavy trucks with a payload of 17 tons
Ethanol Production	
Ethanol Yield	See Table H-1
Steam and Power Generation From Biochemical Plant in 2012	Small industrial boiler used for power generation from residue of switchgrass and corn stover EPA AP-42 emission factors and the National Emissions Inventory for the boiler used (U.S. EPA 1995; 1999)
Criteria Pollutant Emissions From Biorefinery in 2030	RBAEF simulation results (Wu et al. 2005)
Criteria Pollutant Emissions From Biochemical Process in 2012	GREET default values based on EPA's AP-42 report and the National Emissions Inventory used (U.S. EPA 1995; 1999)

Table H-4. Detailed Assumptions: Corn Stover to Ethanol

	Assumptions
Farming Operation	
Corn Yield	Corn yield: 154 bu/acre in 2012; 180 bu/acre in 2030 (Perlack 2006)
Corn Grain Mass to Corn Stover Mass Ratio	1:1
Additional Nitrous Oxide Emissions From Stover Removal	Based on Intergovernmental Panel on Climate Change (1996) Nitrogen content in stover is 0.45% (Sheehan et al. 2002)
Additional nitrogen, Phosphorous, and Potassium Fertilizer Required	0.005 g nitrogen/g stover collected per year (Sheehan et al. 2002)

	Assumptions
Because of Stover Removal	0.0018 g phosphorous/g stover collected per year (Sheehan et al. 2002; Kim and Dale 2005)
	0.0092 g potassium/g stover collected per year (Kim and Dale 2005)
Soil Carbon Change Because of Land Use	Zero (Kim and Dale 2005)
Corn Stover Collection	Operation includes harvesting, bailing, and moving to the edge of field and stack
	Corn and soybean crop rotation for farms and 50% of corn stover available for collection in the year corn is planted (Kim and Dale 2005)
Fuel Use During Stover Collection	Diesel used in this operation
	Fuel use based on stover collection rate by regression model in NREL report (Sheehan et al. 2002)
Lubricant Oil Use	Energy and emissions associated with lubricant oil use during stover collection are small [volume used is less than 1% that of diesel, according to Sheehan et al. (2002)]; they are thus ignored
Corn Stover Transportation From Corn Field to Ethanol Plant	75% acreage use; the 2,000-dry-ton/day ethanol plant is surrounded by farmland in a circular area (Aden et al. 2002)
	Stover bail loaded on a trailer pulled by a heavy truck with payload of 10 short tons, based on stover bail size and bulk density provided by NREL report (Sheehan et al. 2002)
Transportation Distance	21-mile one-way distance in 2012; 33-mile one-way distance in 2030 (based on above assumptions and 2,000 dry tons/day in 2012; 5,000 dry tons/day in 2030)
Ethanol Production	
Ethanol Yield	See Table H-1
Steam and Power Generation in Biochemical Plant in 2012	Same as for switchgrass (Table H-3)
Criteria Pollutant Emissions From Biorefinery in 2030	RBAEF simulation results (Wu et al. 2005)
Criteria Pollutant Emissions From Biochemical Process in 2012	GREET default values based on EPA's AP-42 report

Table H-5. Detailed Assumptions: Forest Residues to Ethanol

	Assumptions
Farming Operation	
Forest Residue Harvesting	Operation includes stumpage and harvesting for pine and hardwood (Hess and Kelley 2006)
Fuel Consumption During Harvesting	4.77 gallons diesel/ton of wood in 2012; 2.38 gallons/ton in 2030 Data derived from operation cost data provided by Idaho National Laboratory (Hess and Kelley 2006) assuming 2003 diesel price
Share of Types of Wood Harvested	2012: pine 54%, hardwood 46%; 2030: pine 59%, hard wood 41% (Haynes 2003)
Transportation From Collection Site to Ethanol Plant	75-mile one-way distance (Hess and Kelley 2006) Heavy trucks with payloads of 17 tons
Ethanol Production	
Ethanol Yield	See Table H-1
Natural Gas Use as Process Fuel	Ethanol production process fed with forest wood (cases 5 and 10) requires natural gas to provide additional heat and power: 45,976 Btu/gallon[a] in 2012; 3,539 Btu/gallon in 2030 (Jechura 2006b)
Heat and Power Generation in Thermochemical Plant in 2012	Natural gas utility industrial boiler (>100 mmBtu/h) used for syngas and natural gas power generation for thermochemical plant Emission factors from EPA AP-42 report
Criteria Pollutants Emissions From Thermochemical Process	Based on NREL (2006) Aspen simulations and GREET default boiler emission factors (AP-42 data) Emissions from thermochemical process were very small (i.e., 10^{-7} g/gallon ethanol); therefore, they were ignored in GREET analysis

[a] This value represents an un-optimized process, and full heat integration for energy efficiency is currently ongoing. Therefore, it is not used in this study. Instead, 3,539 Btu/gallon was assumed for the 2012 woody biomass thermochemical process.

Table H-6. Gasoline-Equivalent Fuel Economy of Light-Duty Vehicles

	Flexible-Fuel Vehicles with E85	Gasoline Vehicles
2012	24.9	24.9
2030	26.6	26.6

Although Table H-6 presents fuel economy for FFVs and gasoline vehicles, the life cycle simulations for ethanol and gasoline were conducted on the basis of per-million British thermal unit of ethanol and gasoline produced and used. Thus, the life cycle analysis results, in the end, were not affected by vehicle fuel economy.

H.1.3.3 Co-Product Credit Allocation

The energy allocation method was used to determine the energy and emission credit for export electricity and chemical co-products (i.e., n-propanol, n-butanol, and n-pentanol) for the cases in which these products were produced with cellulosic ethanol. Energy allocation is based on output product energy share. For each fuel production case, total energy and emissions of bioethanol and co-products were first estimated. Next, their energy shares were determined on the basis of product energy content. Finally, the total energy and emissions from the fuel production process and upstream feedstock activities were allocated by multiplying the total energy and emissions by their energy shares.

The energy allocation approach tends to be conservative in determining energy and emission credits for electricity. This approach treats all energy products from the production process as equal—regardless of form and quality differences. The complexity of this issue is recognized. Until additional data become available and resources allow for other methods (such as the displacement method), the allocation approach is appropriate for this study.

Methanol is consumed internally in ethanol plants; therefore, it is not treated as a co-product. The energy partitioning results serve as GREET inputs. Table H-7 lists the output energy shares (as percentages) for each production option. The energy shares were calculated from ASPEN Plus results (Table H-1).

Table H-7. Energy Allocation for Ethanol, Electricity, and Chemicals

Case		Output Energy Share (%)		
		Ethanol	**Electricity**	**Chemicals**
Case 3:	Switchgrass to Ethanol Through Biochemical Conversion	84.48	16.22	0
Case 4:	Corn Stover to Ethanol Through Biochemical Conversion	91.20	8.80	0
Case 5:	Forest Residues to Mixed Alcohols Through Thermochemical Conversion	73.75	NA[a]	26.25%
Case 8:	Switchgrass to Ethanol Through Biochemical and GTCC	79.6	20.4	0
Case 9:	Corn Stover to Ethanol Through Biochemical and GTCC	79.6	20.4	0
Case 10:	Forest Residues to Mixed Alcohols Through Biochemical/Thermochemical Biorefinery	91.45	5.42	3.13%

[a] NA = Not applicable; this option requires grid electricity input.

H.1.4 WTW Results

H.1.4.1 Energy Use and GHG Emissions

Figures H-6 and H-7 present WTW fossil energy and petroleum energy consumption per million British thermal unit of fuel produced and used for each of the 10 cases. Corn grain and stover- and switchgrass-based ethanol scenarios achieve substantial reductions in petroleum energy use (more than 90% compared with gasoline; see Figure H-6) in both 2012 and 2030. Savings for the forest residue case are 80%–86%. The reduced petroleum savings by forest residue-based ethanol are primarily the result of diesel use for forest wood harvesting, collection, and transportation. Furthermore, for the forest residues case, hardwood operations require about 25% more fuel than do softwood operations. Therefore, when the share of hardwood decreases in 2030 (Table H-5), diesel fuel use will decrease for the forest residue-based ethanol case.

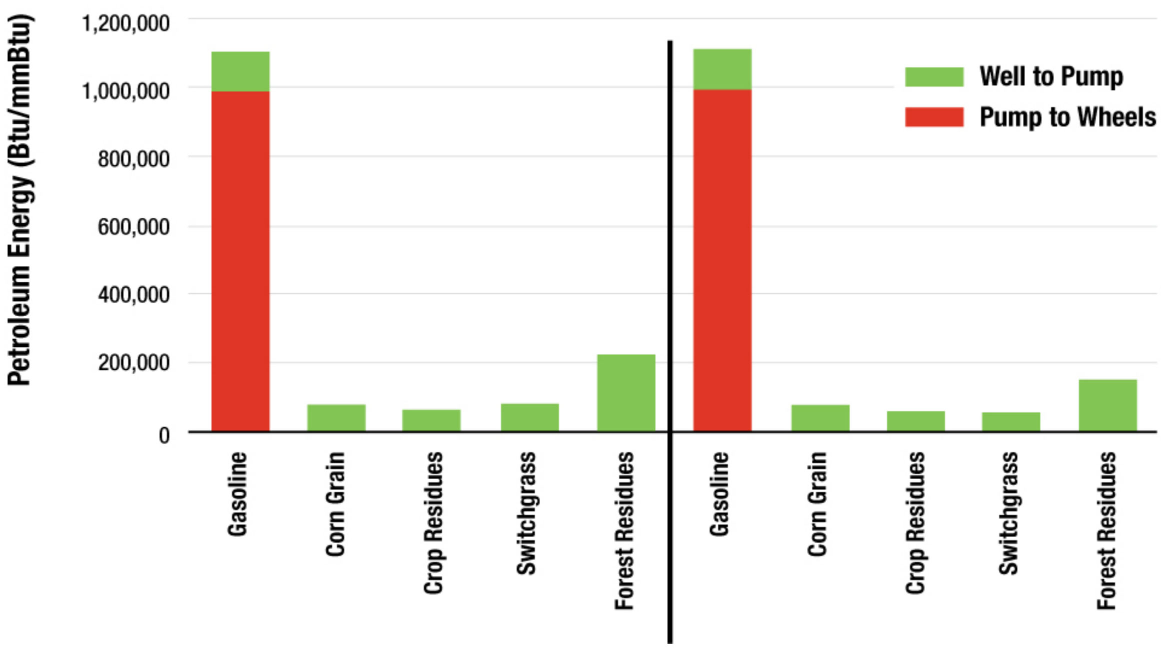


Figure H-6. WTW Petroleum Energy Use by Bioethanol Case Compared with Gasoline in 2012 and 2030

For fossil energy use (see Figure H-7), although each biofuel case shows a net reduction compared with gasoline, the differences among biofuel options are quite large. Corn ethanol achieves a moderate reduction (about 40%), while cellulosic ethanol cases could reduce fossil fuel use by an additional 30%–50%. This is because lignin is burned in cellulosic ethanol plants to meet internal power and heat demands. (In corn ethanol plants, coal or natural gas is burned to provide heat and power, which contributes to fossil energy use).

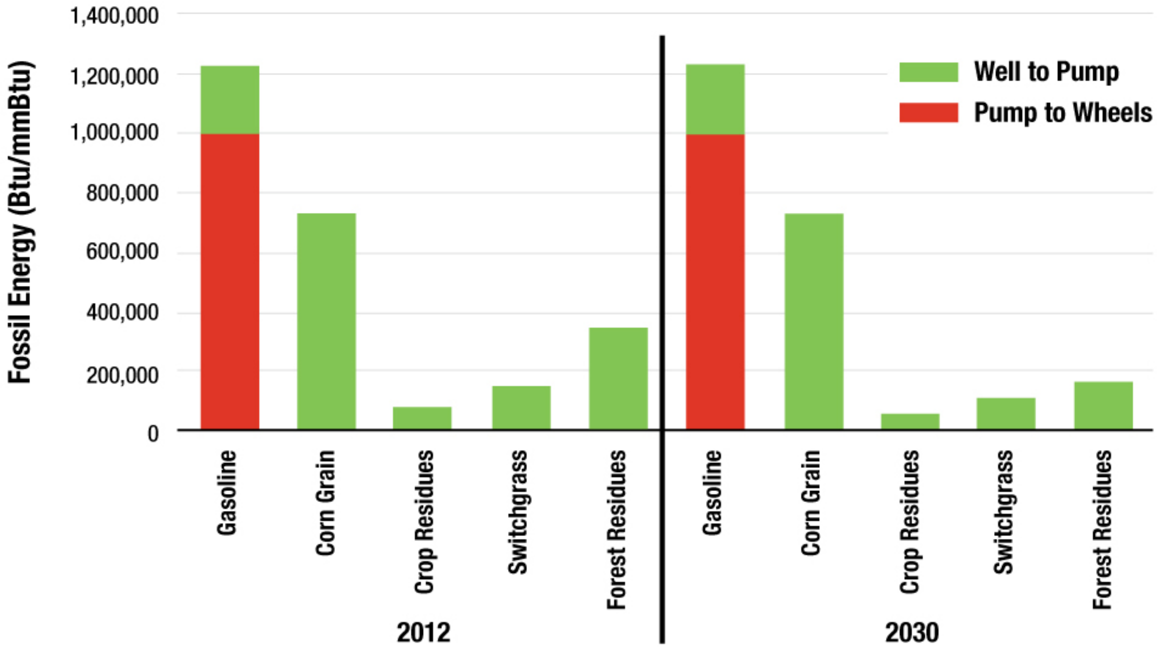


Figure H-7. WTW Fossil Energy Use by Bioethanol Case Compared with Gasoline in 2012 and 2030

There is a marked reduction in fossil energy use in the forest residue cases from the near-term (Case 5) to the long-term (Case 10). In 2012, forest residue-based ethanol is produced through a thermochemical process that requires natural gas and grid electricity input. The woody ethanol production in 2030 is through a biochemical-thermochemical biorefinery, in which the ethanol plant becomes a net electricity exporter and, thus, reduces fossil energy use.

Apparent high fossil energy savings by corn stover is partially attributable to the fact that the baseline fertilizer use in corn fields is allocated to corn grains, as indicated in Section H.1.3.3. The nitrogen fertilizer production process is the major fossil fuel use for farming operations.

Regardless of the feedstocks and ethanol production process, cellulosic ethanol could reduce GHG emissions by 80%–88% in 2012 and up to 96% in 2030 (see Figure H-8). Ethanol produced from forest residues in 2030 could reduce GHG emissions by an additional 16%, which is also an attribute of the biochemical-thermochemical biorefinery process. Biorefinery production of cellulosic ethanol from corn stover and switchgrass also contributes to GHG emission reductions. The GHG emissions reductions for the corn ethanol cases are moderate (24%–25%). GHG emissions here are carbon dioxide-equivalent emissions of carbon dioxide, nitrous oxide, and methane, weighted with their global warming potentials (1, 23, and 296, respectively).

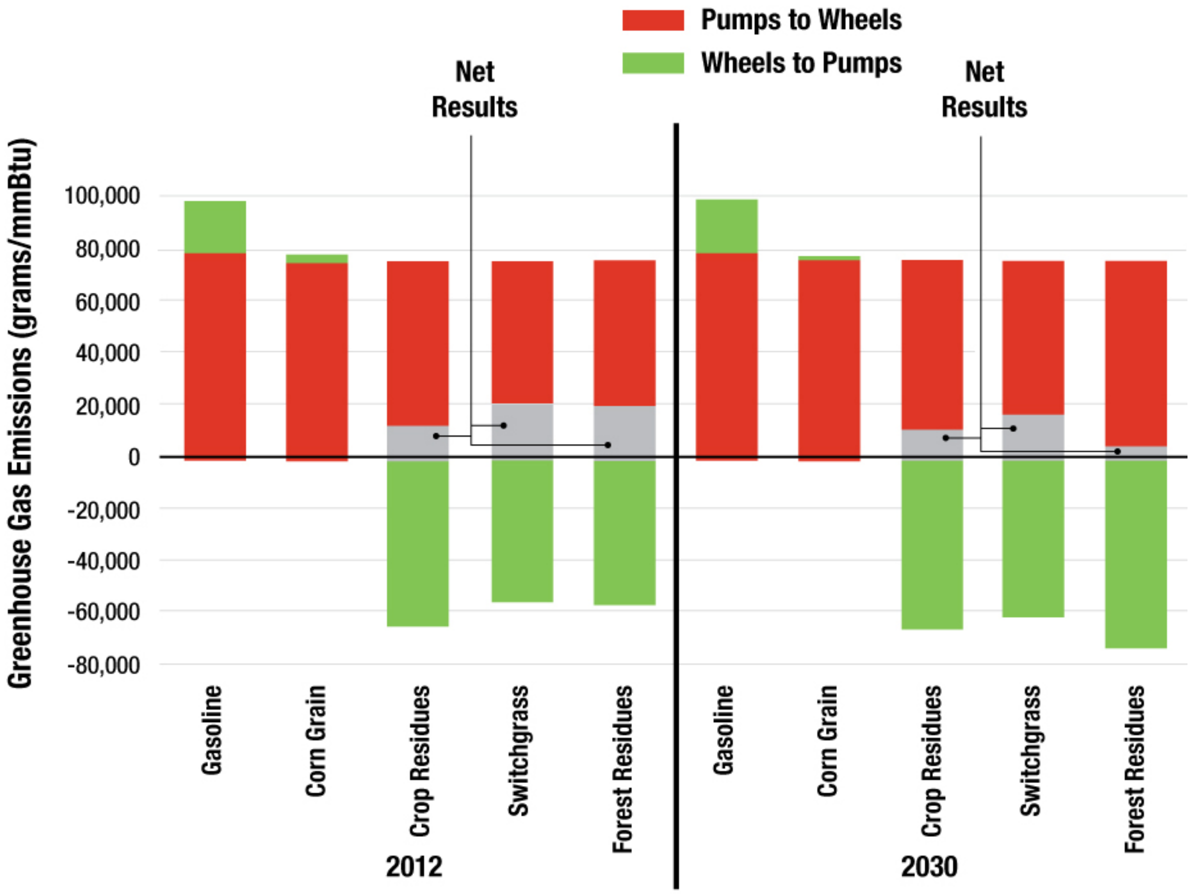


Figure H-8. WTW GHG Emissions by Bioethanol Case Compared with Gasoline in 2012 and 2030

(Net results here are the sum of WTP and PTW emissions. A positive value means net emissions, and a negative value means a net uptake of carbon dioxide from the air.)

WTW results for carbon dioxide emissions only are presented in Figure H-9. The carbon dioxide data are presented to allow comparison with the results from other studies, which only estimate carbon dioxide emissions. Apparently, ignoring nitrous oxide and methane emissions gives fuel ethanol some unwarranted additional benefits.

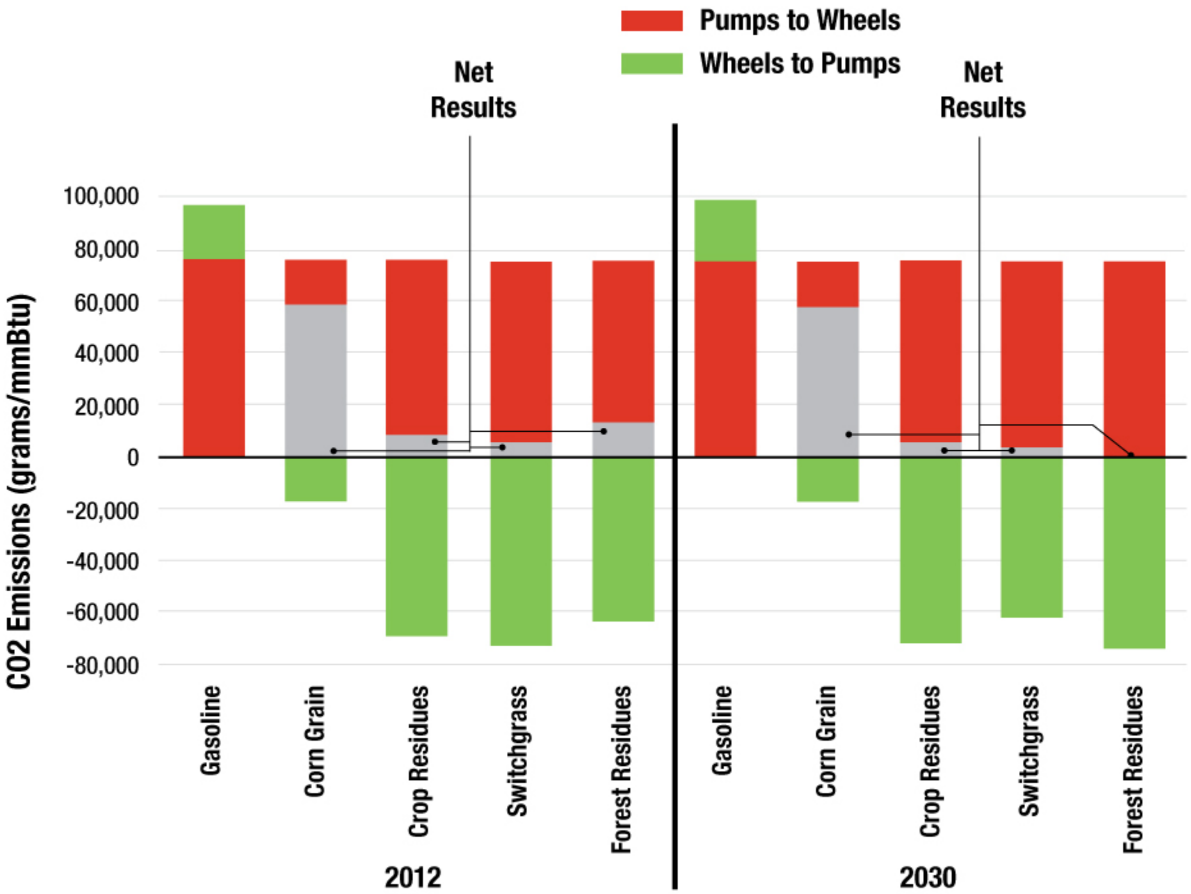


Figure H-9. WTW Carbon Dioxide Emissions by Bioethanol Case Compared with Gasoline in 2012 and 2030

(Net results here are the sum of WTP and PTW emissions. A positive value means net emissions, and a negative value means a net uptake of carbon dioxide from the air.)

H.1.4.2 Criteria Pollutant Emissions

Criteria pollutant emissions results are presented in figures H-10 through H-19. These emissions are separated into total and urban emissions. Urban emissions have long been an environmental and health concern because of their potential for human population exposure. Total emissions are the sum of urban and rural emissions.

Results show across-the-board net reductions in urban criteria pollutant emissions by ethanol, with the exception of carbon monoxide (no change), relative to gasoline. This can be explained by the location of bioethanol plants. Corn and cellulosic ethanol plants are most likely to be built near farms to minimize feedstock transportation costs. Criteria pollutants emitted from farming, feedstock transportation, and ethanol production steps contribute to rural emissions only. In contrast, a sizable portion of petroleum refineries (up to 60%) are situated in or near urban areas, which results in a high share of urban emissions.

The figures show that biorefineries that incorporate biochemical and thermochemical processes with integrated heat and power generation could avoid significant total sulfur oxide, nitrogen oxide, PM_{10}, and VOC emissions. For example, the production step for the forest residue-based ethanol case in 2030 results in total sulfur oxide emissions that are 86% lower than those in 2012—a direct result of the biochemical-thermochemical biorefinery (see figures H-18 and H-19). This refinery design is responsible for half of the reduction in total nitrogen oxide emissions from 2012 to 2030 (see figures H-14 and H-15).

For corn stover- and switchgrass-based cases, additional 77%–80% reductions in total nitrogen oxide emissions from 2012 to 2030 are attributable to the switch from biochemical conversion plants to biorefinery plants. The reductions in nitrogen oxide emissions between 2012 and 2030 are also achieved by reduced diesel use during wood harvesting and transportation; reduced emissions from combustion technologies fueled with natural gas-, coal-, and petroleum-based fuels during feedstock farming and ethanol production; and reduced tailpipe emissions from vehicles in 2030.

The trend for PM_{10} emissions closely follows that of nitrogen oxide emissions. Total PM_{10} emissions decrease 63%–71% from 2012 to 2030; the majority of the decrease results from the change to biorefinery production.

Similarly, total VOC emissions decrease 14%–25% from 2012 to 2030 for the three cellulosic ethanol cases (see figures H-10 and H-11). Results suggest that, with a well-integrated heat and power cogeneration ethanol production plant, net reductions of total sulfur oxides and PM_{10} could be realized for corn stover-, switchgrass-, and forest residue-based ethanol.

A potential problem with the cellulosic ethanol production cases is an increase in total emissions of VOCs, carbon monoxide, PM_{10}, and nitrogen oxide in the near term (i.e., 2012), although these emissions are reduced significantly in 2030 because of the use of advanced ethanol production technologies. The only exception is sulfur oxide emissions from corn stover- and switchgrass-derived ethanol. Ethanol produced from biochemical processes with these two feedstocks outperformed other ethanol-feedstock combinations and achieved 37%–45% reductions in total sulfur oxide emissions in 2012 relative to the sulfur oxide emissions of gasoline.

Corn-based ethanol shows increased emissions of criteria pollutants in both 2012 and 2030. The corn ethanol plants analyzed employ a conventional fermentation process that relies on coal and natural gas-fired combustion systems to supply heat and on-grid electricity (U.S. mix) to supply power. The U.S. electricity mix is produced from a mixture of coal (50%), natural gas (20%), and other sources. The heat and power supply is responsible for the major criteria pollutants emissions: nitrogen oxide (from natural gas and coal), PM_{10} (from coal), and sulfur oxide (from coal).

From the figures with results for 2030, readers may mistakenly conclude that the corn-based ethanol cases have worse results than cellulosic ethanol cases. This is only because different scales are used for 2012 and 2030 for the same pollutant in the cellulosic ethanol cases. In fact, criteria pollutant emissions associated with corn-based ethanol remain relatively constant between 2012 and 2030 while those of cellulosic ethanol are reduced significantly between 2012 and 2030.

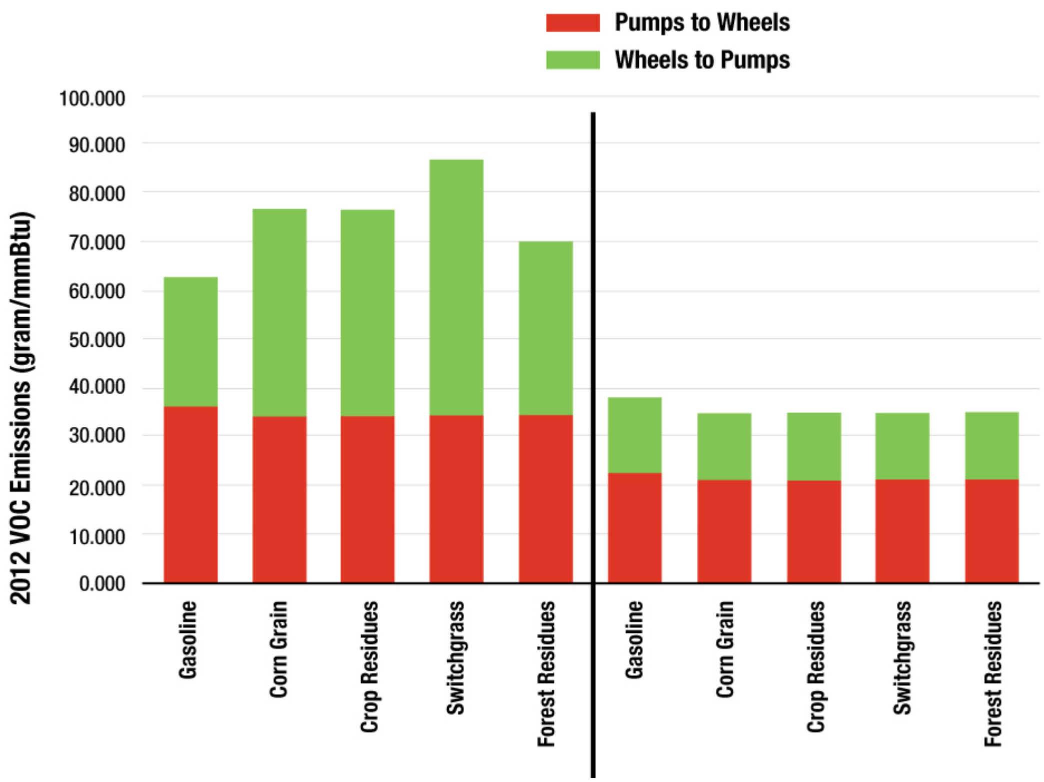


Figure H-10. WTW Total and Yrban VOC Emissions by Bioethanol Case Compared with Gasoline in 2012

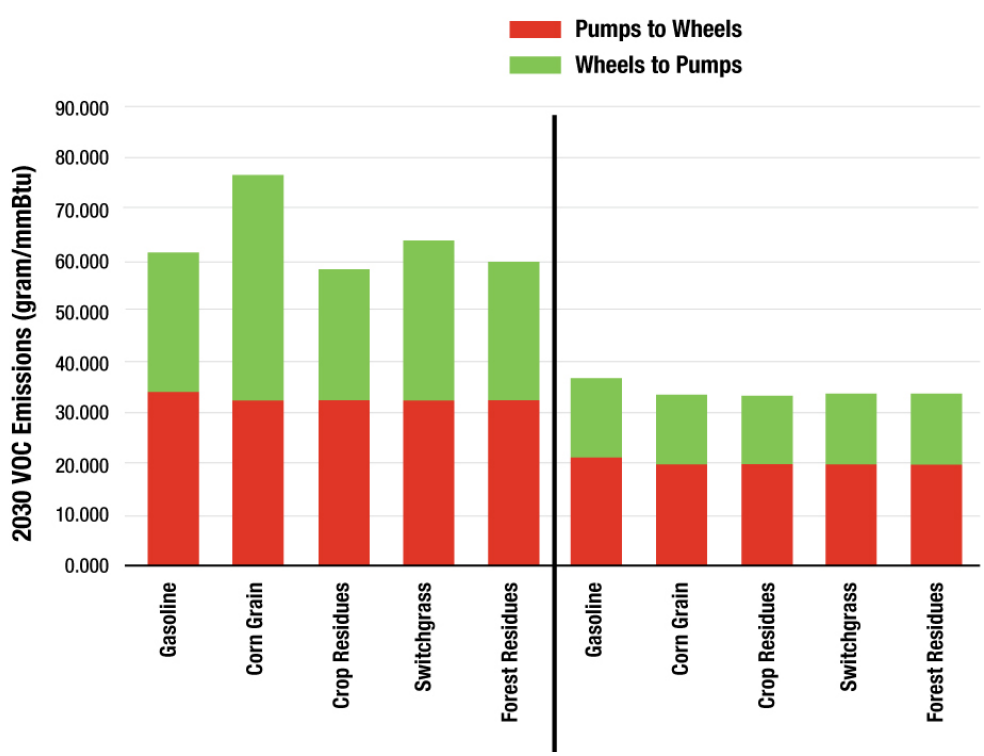


Figure H-11. WTW Total and Urban VOC Emissions by Bioethanol Case Compared with Gasoline in 2030

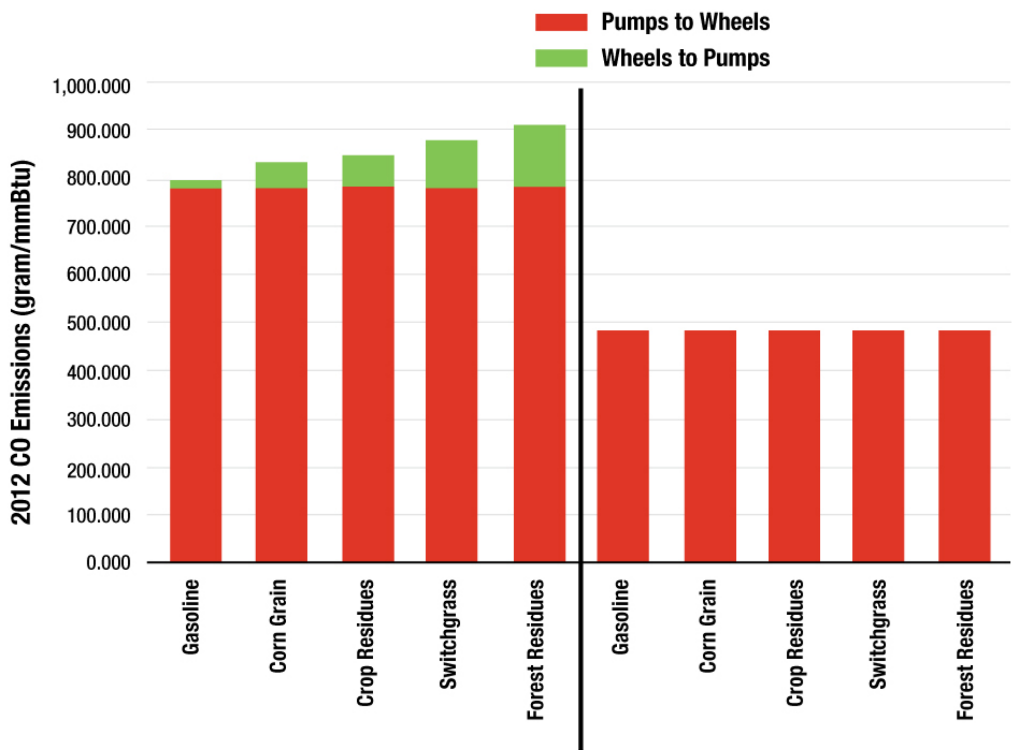


Figure H-12. WTW Total and Urban Carbon Monoxide Emissions by Bioethanol Case Compared with Gasoline in 2012

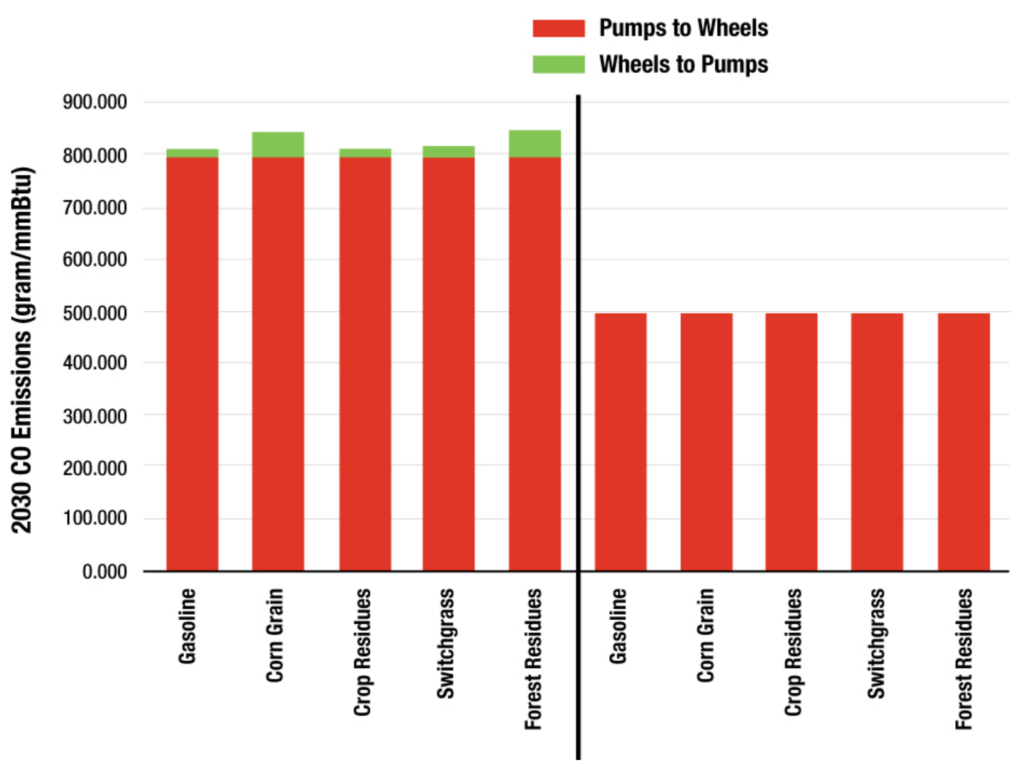


Figure H-13. WTW Total and Urban Carbon Monoxide Emissions by Bioethanol Case Compared with Gasoline in 2030

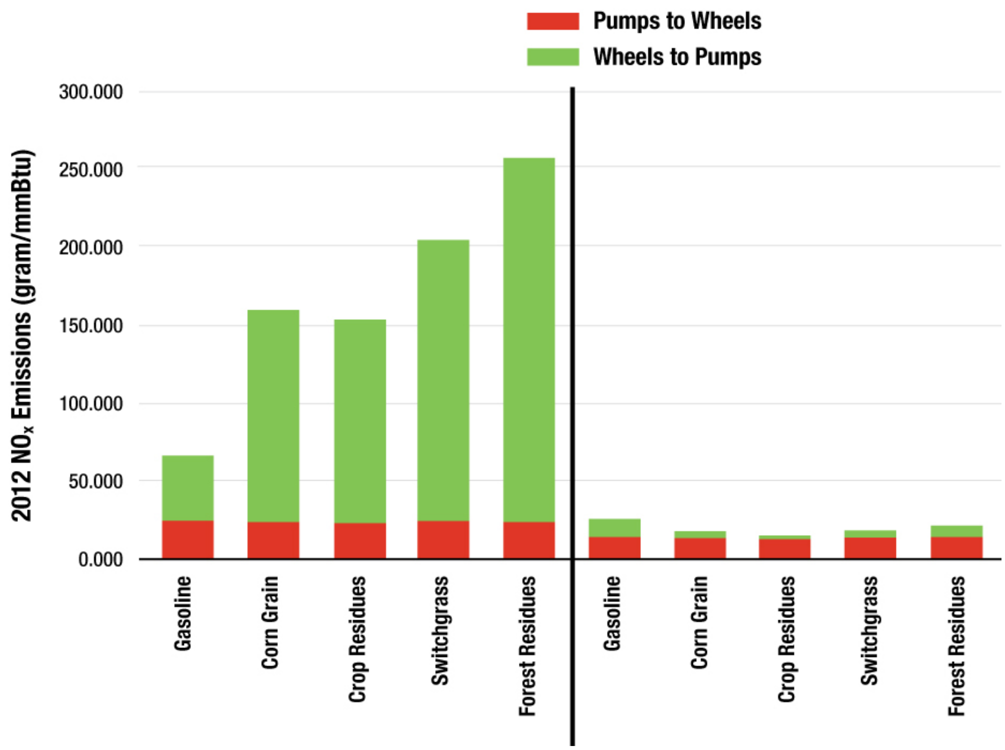


Figure H-14. WTW Total and Urban Nitrogen Oxide Emissions by Bioethanol Case Compared with Gasoline in 2012

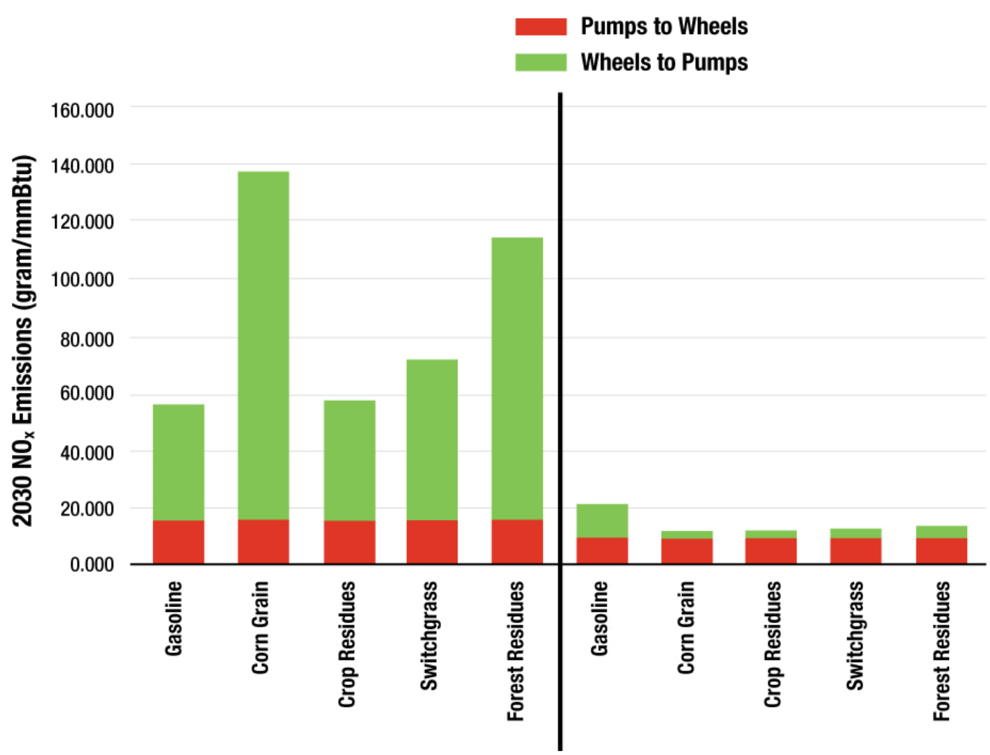


Figure H-15. WTW Total and Urban Nitrogen Oxide Emissions by Bioethanol Case Compared with Gasoline in 2030

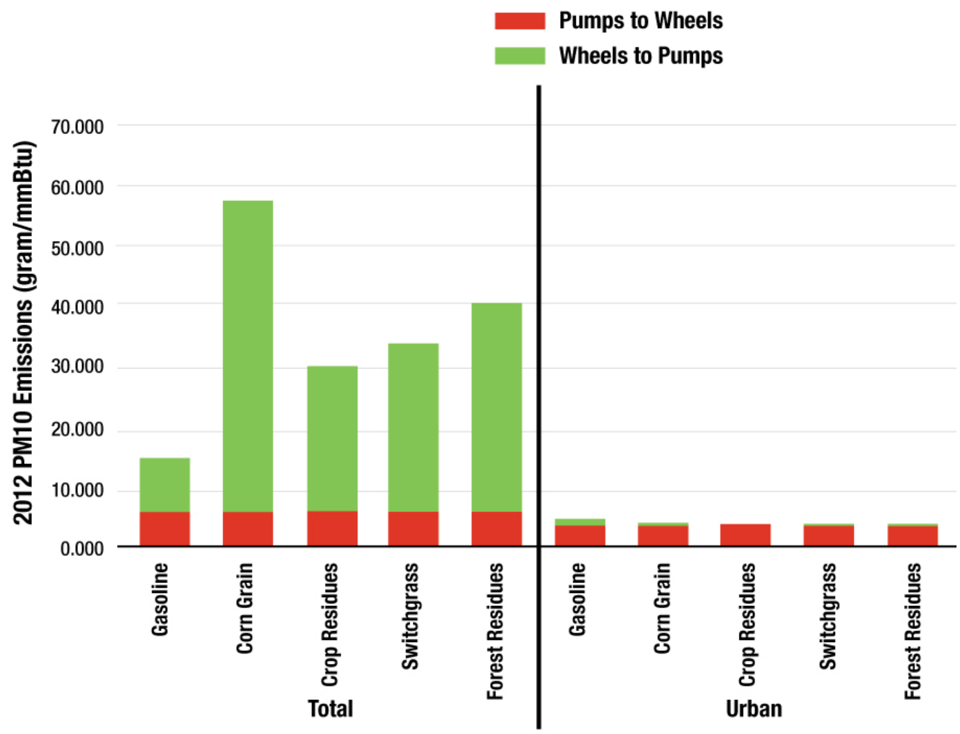


Figure H-16. WTW Total and Urban PM_{10} Emissions by Bioethanol Case Compared with Gasoline in 2012

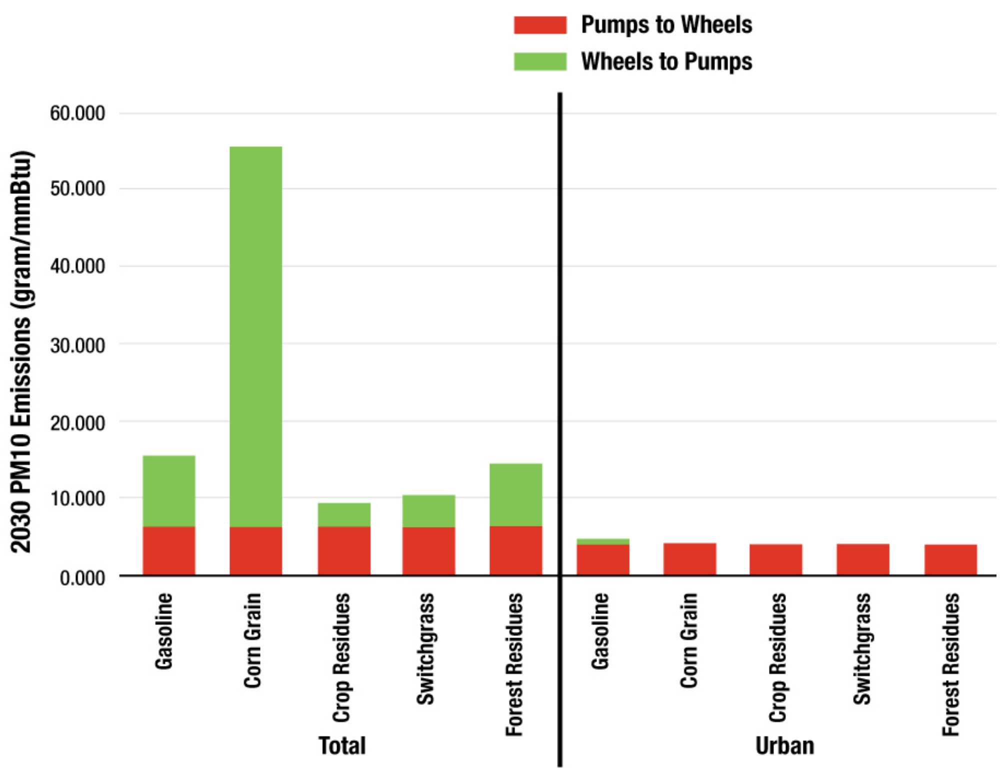


Figure H-17. WTW Total and Urban PM_{10} Emissions by Bioethanol Case Compared with Gasoline in 2030

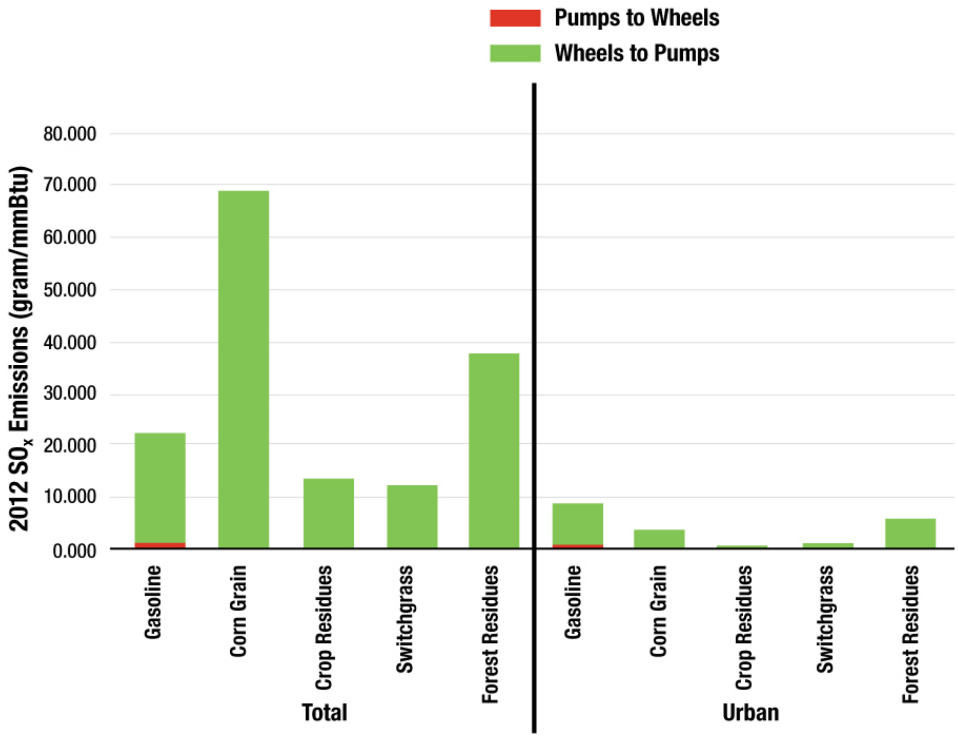


Figure H-18. WTW Total and Urban Sulfur Oxide Emissions by Bioethanol Case Compared with Gasoline in 2012

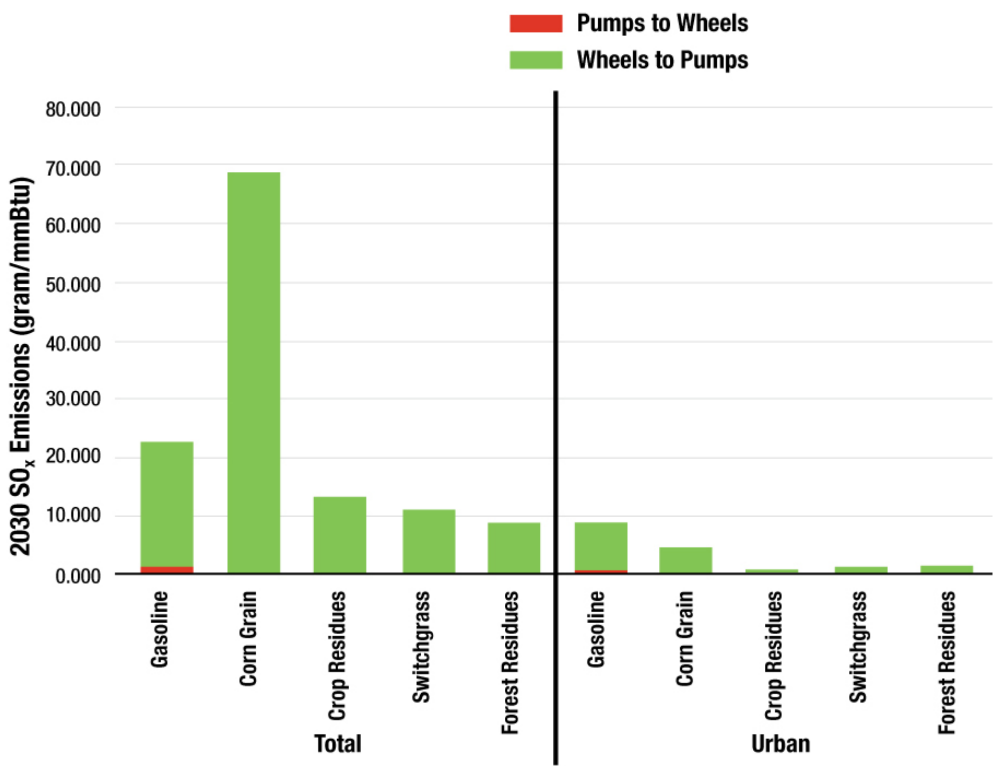


Figure H-19. WTW Total and Urban Sulfur Oxide Emissions by Bioethanol Case Compared with Gasoline in 2030

H.2 Estimation of Annual Reductions in Oil Use and GHG Emissions by Ethanol Use in Light-Duty Vehicles through the VISION Model

The previous section presented estimates of WTW energy and emissions of producing and using one million British thermal units of bioethanol versus gasoline. This section presents estimates of annual reductions in oil use and GHG emissions as a result of using ethanol in the U.S. light-duty vehicle fleet by applying the WTW results per unit of ethanol from the previous section and annual ethanol supply for the 30x30 scenario

NREL provided two sets of annual ethanol supply projections. Argonne's VISION model was then used to simulate the effects of increased ethanol use in light-duty vehicles on energy use and GHG emissions.

The VISION model was used to generate ethanol demand by motor vehicles to match ethanol supply under the two ethanol-supply cases. The VISION model uses vehicle survival and age-dependent usage procedures to track vintage-specific vehicle stock and usage. The model develops estimates of light- and heavy-duty vehicle stock composition, vehicle miles traveled, and energy use. The current version of the model can simulate conventional vehicles as well as six new-technology vehicles (Singh, Vyas, and Steiner 2004). The model was calibrated to annually match the EIA's projections in its 2006 *Annual Energy Outlook*, which covers up to 2030. The EIA's projections were extended to 2050 through a collaborative effort with DOE EERE Office of Planning and Budget Analysis. EERE has used the VISION model extensively to evaluate the impacts of new technology.

H.2.1 Ethanol Supply

The ethanol supply projections for the 30x30 scenario were evaluated to determine the inputs to the VISION model. The two sets of estimates are shown in Figure H-20. The low ethanol supply case was developed under the reference case of the EIA 2006 *Annual Energy Outlook* (EIA 2006a), and the high ethanol supply case was developed under the high oil price case of the 2006 *Annual Energy Outlook*. As Figure H-20 shows, ethanol supply rises slowly during 2005–2014. The supply then remains nearly stable for almost 8 years before beginning to rise significantly.

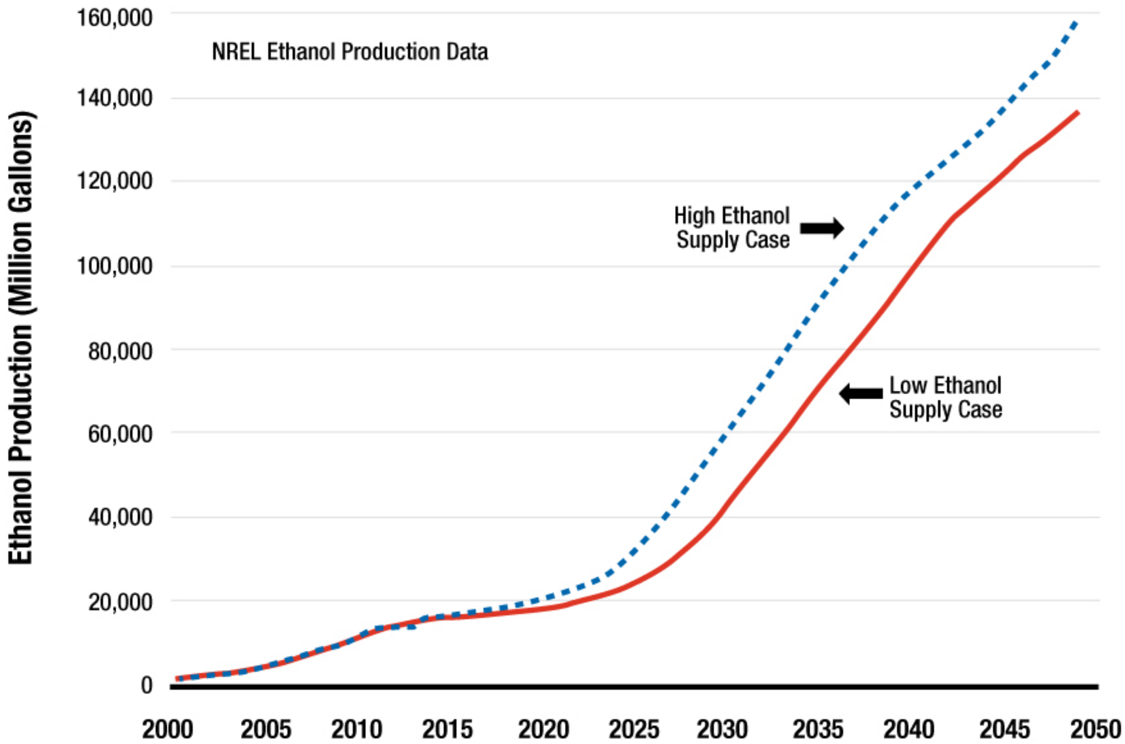


Figure H-20. Ethanol Estimates

H.2.2 VISION Inputs

In the design of VISION simulations, it was assumed that during the period through 2022, ethanol would be used by FFVs designed to use either E85 or gasoline. With this assumption, the FFV market penetration schemes were developed for both ethanol supply cases so that at any year between 2010 and 2050, the amount of ethanol supplied would be consumed by light-duty vehicles.

The ethanol use in light-duty vehicles would occur two ways:

- In low-level blends (10% or less by volume) with gasoline for use by conventional vehicles
- In high-level blends (up to 85% by volume) for use by FFVs.

As of now, the low-level ethanol blends are E5.7 in California and E10 in the rest of the country. On average, about 30%–40% of U.S. gasoline is blended with ethanol at low levels. The majority of ethanol is now used in low-level blends. Ethanol use in E85 for FFVs is tiny.

For VISION simulations, a penetration scheme of low-level blends in the gasoline market was developed. It assumed that by 2020, all gasoline will contain 10% ethanol. Table H-8 shows the percent of fuel ethanol of the total gasoline market with the low-level blend market. As the table shows, the volumetric share of ethanol in the form of low-level blends increases slowly from 1.5% in 2000 to 10% in 2020.

Table H-8. Fuel Ethanol Share of Motor Gasoline for Use in Low-Level Ethanol Blends by Conventional Vehicles

Year	Ethanol Share (%)	Year	Ethanol Share (%)
2000	1.5	2010	4.5
2001	1.7	2011	4.9
2002	2.0	2012	5.3
2003	2.3	2013	5.7
2004	2.6	2014	6.2
2005	3.0	2015	6.7
2006	3.3	2016	7.3
2007	3.5	2017	7.9
2008	3.8	2018	8.5
2009	4.1	2019	9.2
		2020–2050	10.0

(Data for 2000–2005 were to match ethanol use; data for 2006 and on were based on a penetration of ethanol use in low-level blends to 10% of the gasoline market by 2020.)

After taking into account the low-level ethanol blend market, market penetration profiles were then specified for new FFVs to use high-level blends up to E85. It was assumed that, when available, these vehicles will use E85 fuel. However, because of fluctuations in ethanol production, they may not always use E85. The resulting average fuel ethanol share of FFV fuel could be less than 85% by volume, depending on the ethanol supply in a given year.

It was also assumed that E85 FFVs would have the same fuel economy, on a British thermal unit basis, as conventional vehicles.

The projections were assumed to represent neat ethanol. All calculations assume that fuel ethanol contains 5% gasoline as the denaturant. Thus, ethanol production projections represented 95% of fuel ethanol that would be made available.

The E85 FFV market penetration profiles were developed on the basis that the resulting FFV stock in a given year would consume the supply volume of ethanol for the given year projected. FFVs have been on the market since the late 1990s. The EIA provides the number of ethanol FFVs made available (EIA 2006). Data relating to sales through 2004 were used. On the basis of press releases by automakers and personal conversations with auto industry representatives, new light-duty FFV sales through the year 2010 were estimated. After 2010, two new FFV sales profiles were developed for the period 2011–2050 by fitting logic models to generate enough ethanol demand to consume the ethanol supply under the two ethanol-supply cases (minus the ethanol demand by the low-level blend market). Although it would be difficult to exactly match ethanol production estimates if all FFVs use E85 only, it was assumed that the ethanol content of FFV fuel would vary, depending on ethanol availability in a given year. This simulation logic reflects the reality of FFV operations, as long as E85 is cost-competitive. With this assumption, the market penetration profile would provide ethanol consumption estimates very similar to production estimates.

Figure H-21 shows FFV market penetration profiles used in this analysis. Under the low ethanol supply case, FFV share of the new vehicle market increases slowly, reaches the 50% level in 2038, and has a 57% share by 2050. Under the high ethanol supply case, the 50% market share is achieved by 2032, and the 2050 share is 67%. Current policy discussion suggests that automakers could be required to produce FFV shares much larger and faster than these FFV penetration schemes suggest—the latter reflects the constraint of ethanol supply. This result implies that ethanol supply, not ethanol demand by FFVs, will be the constraint on the future fuel ethanol market.

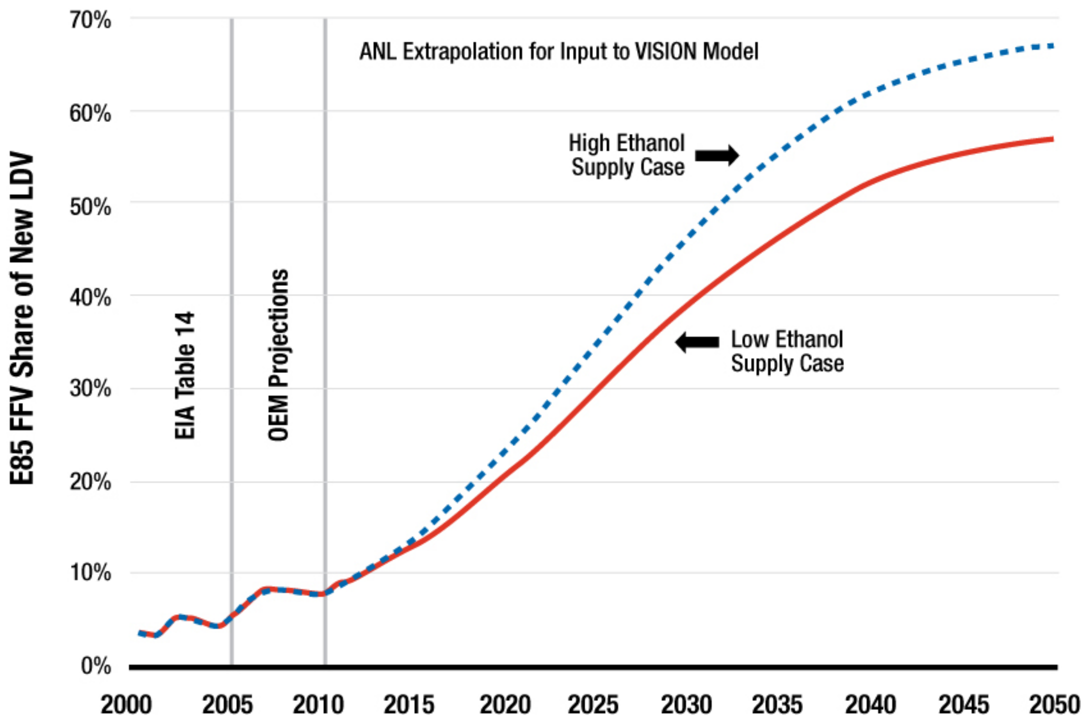


Figure H-21. Assumed E85 FFV Market Penetrations of the New Light-duty Vehicle Market

H.2.3 VISION Results

The VISION model was executed, and its energy use results were analyzed. The ethanol production estimates, as shown in Figure H-20, rise through 2014 and are nearly stable during 2014–2022. During 2000–2020, fuel ethanol share of blended gasoline also rises. Even with the rising ethanol content of gasoline for use by conventional vehicles, some E85 FFVs must be on the road to consume the available fuel ethanol. The light-duty vehicles have very high survival probability through the first 10 years. Consequently, the FFVs sold during 2000–2014 may not have enough fuel ethanol available to operate at 85% volume when ethanol production stabilizes during 2014–2022. In this situation, it was assumed that FFVs would use ethanol blends lower than 85% ethanol or that some of the FFVs may operate on gasoline only (as most of FFVs do now). In the end, the ethanol consumption will match the production estimates, but the average ethanol content of FFV fuel may be less than 85%.

Figures H-22 and H-23 show ethanol use patterns projected by VISION under the two ethanol supply cases. The upper curves in the figures show the pattern of ethanol consumption if all FFVs could use fuel ethanol at 85%. The lower curve shows the pattern of ethanol consumption that matches the production estimate by assuming that all FFVs use ethanol blends lower than E85.

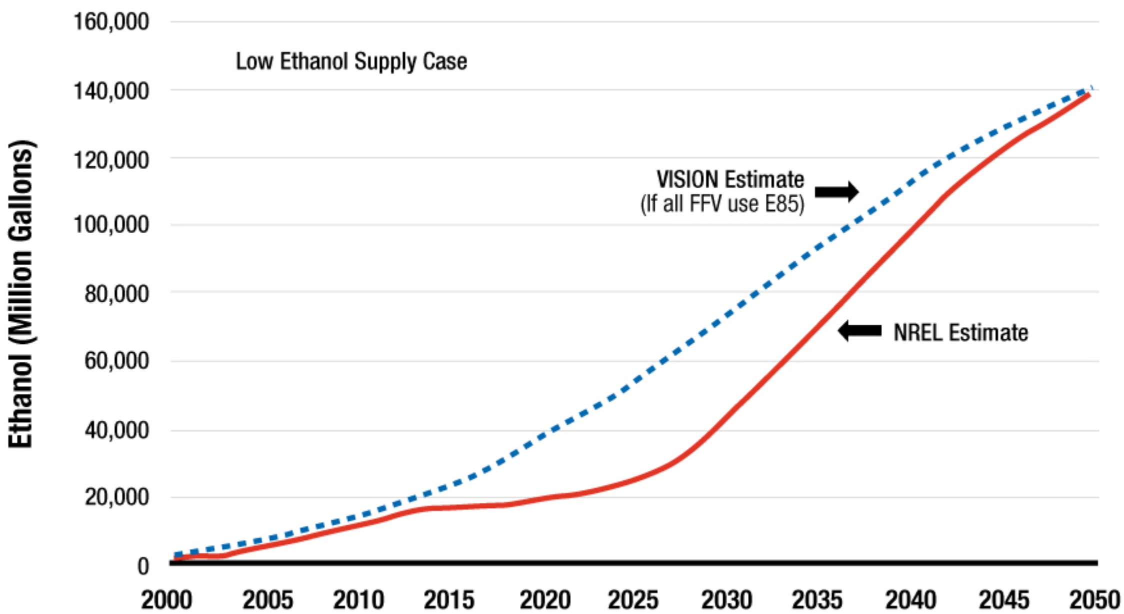


Figure H-22. Ethanol Consumption Patterns from VISION – low ethanol supply case

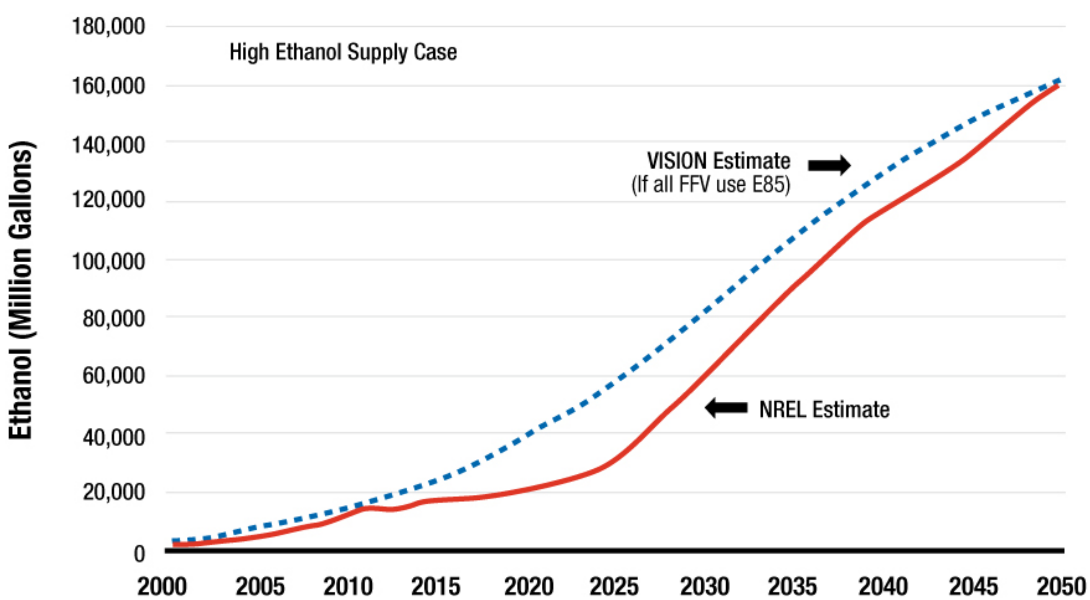


Figure H-23. Ethanol Consumption Patterns from VISION – high ethanol supply case

The difference between the VISION-estimated ethanol demand and NREL-estimated ethanol supply in each of the figures shows that larger volumes of E85 will be used if all FFVs operate on E85, as assumed under the FFV market penetration schemes shown in Figure H-21. The gap between ethanol production and ethanol consumption is very small through 2012. It then widens after 2012 and closes by 2050. The shortfall (i.e., the difference between ethanol demand if all FFVs use E85 and the production estimate) under the low ethanol supply case is wider than that of the high ethanol supply case.

The average ethanol contents of FFV fuel were estimated under both cases. Figures H-24 and H-25 show average ethanol contents of FFV fuel and actual ethanol consumption by FFVs under the two cases. Under the low ethanol supply case, the average volume of fuel ethanol rises to 61% by 2012 (see Figure H-24) and then drops as ethanol production stagnates. Because more FFVs continue to be sold with very little increase in ethanol fuel production, the average ethanol volume drops to 21% by 2020. The average ethanol volume then rises as more ethanol is produced. The implication is that, to fully take advantage of the FFVs already on the road, ethanol production should increase during this period. Under the high ethanol supply case, the average ethanol volume rises to 66% by 2011 (see Figure H-25) and then suddenly drops. The V-shaped drop is caused by a sudden change in ethanol supply (see Figure H-20). The average ethanol volume in FFV fuel drops to 27% by 2020 and then starts rising to 85% by 2050.

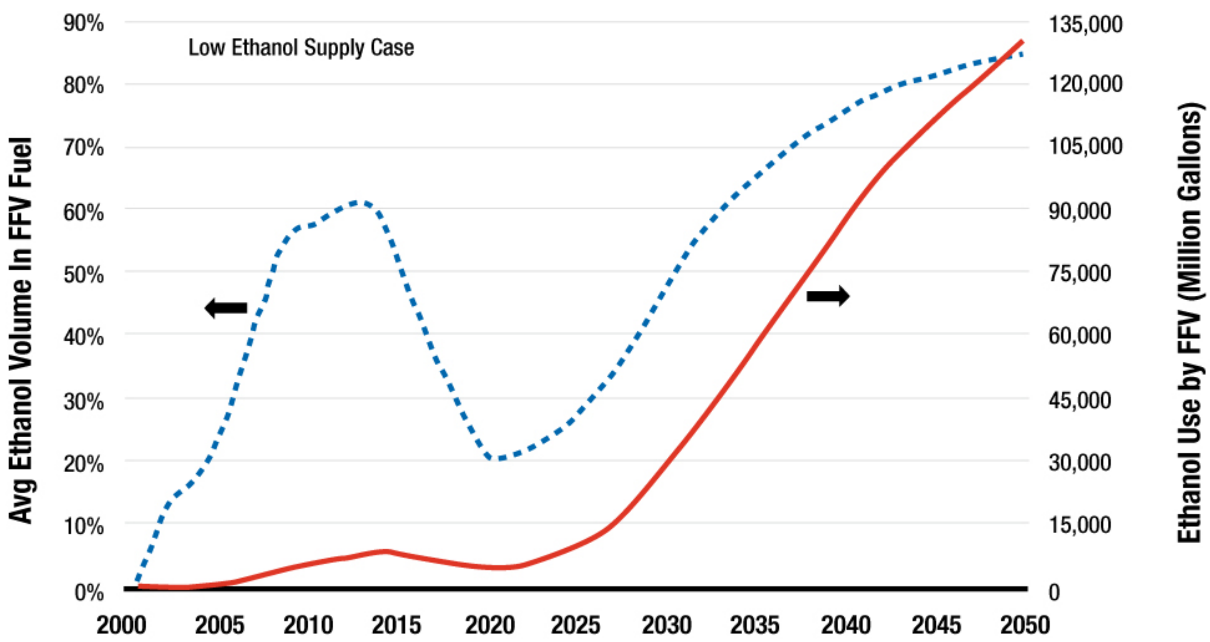


Figure H-24. Average Ethanol Share in FFV Fuel and FFV Ethanol Use under the Low Ethanol Supply Case

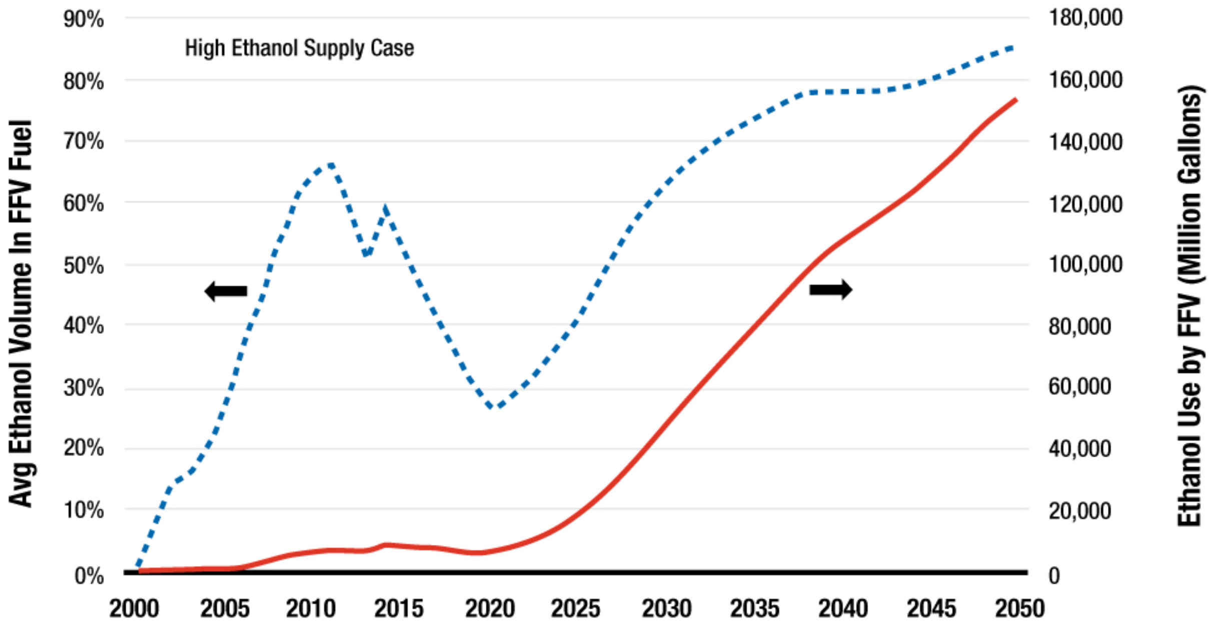


Figure H-25. Average Ethanol Share in FFV Fuel and FFV Ethanol Use under the High Ethanol Supply Case

The projected total ethanol demand is made up of low-level ethanol blends for use by conventional vehicles and higher-level ethanol blend for use by FFVs. Figures H-26 and H-27 show that the low-level blend would use only a small amount of ethanol after 2025. As ethanol production increases, FFVs capable of using E85 are necessary to consume the remaining ethanol supply. The implication is that in the future, FFVs and E85 refueling stations will have to be introduced to accommodate the volume of potential ethanol supply. Under the low ethanol supply case, ethanol use by FFVs rises through 2014 and then stays below the 2014 volume for 9 years before rising again. Under the high ethanol supply case, the FFV ethanol use pattern is different. The FFV use of ethanol rises through 2011, drops for 2 years, rises for 1 year, and then stays below the 2014 volume through 2021 before rising again.

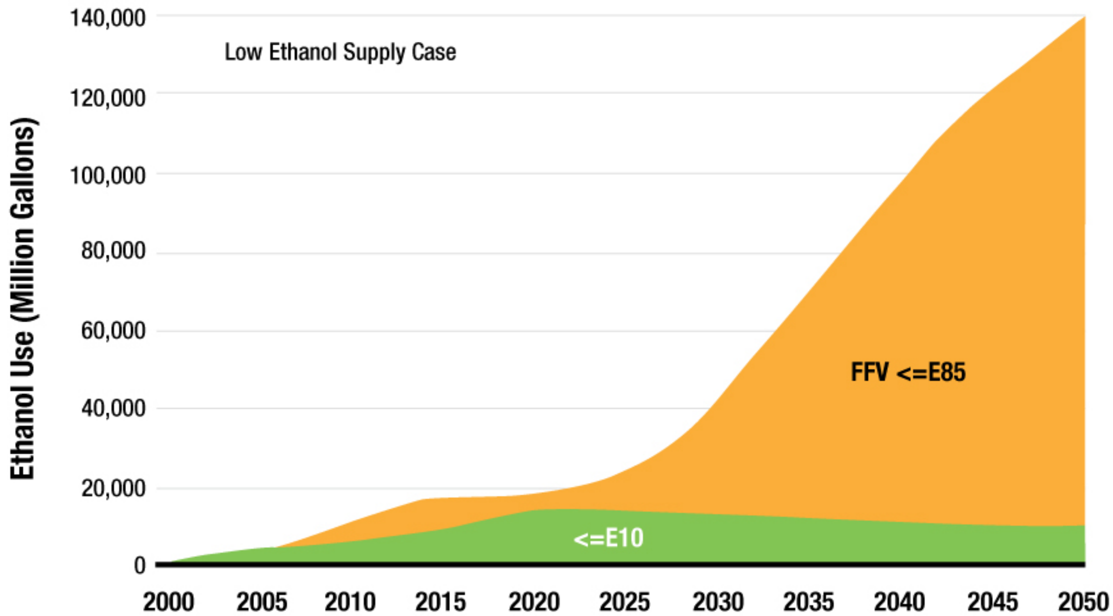


Figure H-26. VISION-projected Ethanol Volumes used in E10 and E85 Fuels – low ethanol supply case

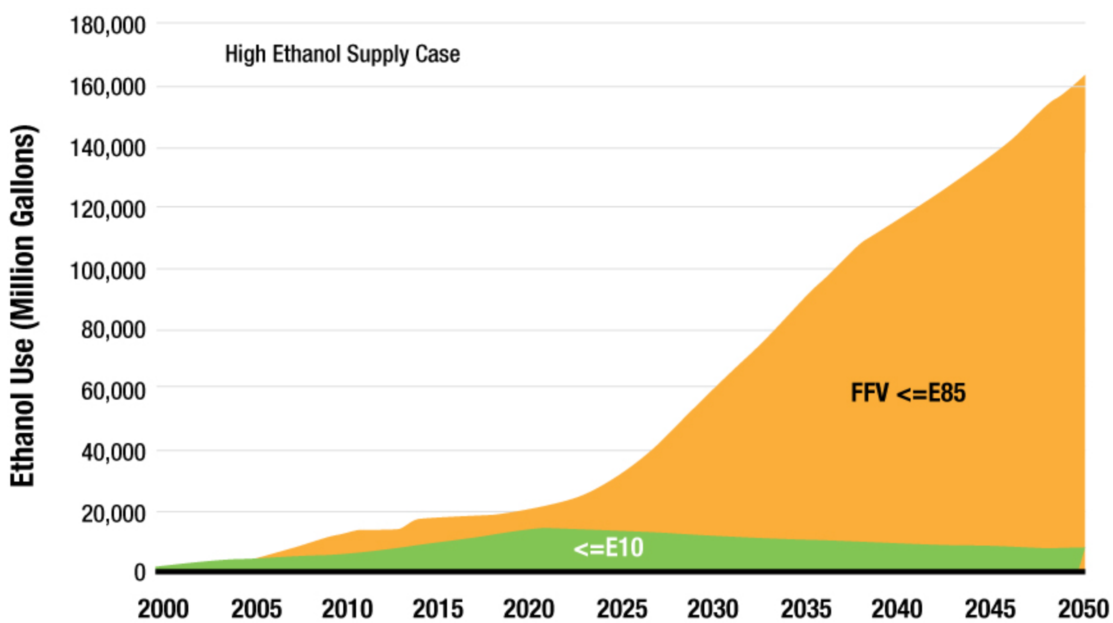


Figure H-27. VISION-projected Ethanol Volumes used in E10 and E85 Fuels – high ethanol supply case

The VISION model also projected the number of FFVs on the road. It computed their share of the total light-duty vehicle stock and analyzed it. Figure H-28 shows the number of FFVs on road under the two ethanol-supply cases. The numbers of FFVs on the road are nearly the same for the first 15 years under the two ethanol-supply cases. They diverge only after 2018.

This outcome is expected because new FFV sales were very similar through 2013, and small differences after that were not significant enough to show visible change from the surviving prior-year FFVs. The number of FFVs on the road reaches 207 million under the low ethanol supply case and 244 million under the high ethanol supply case.

Their share of light-duty vehicles was also analyzed. The FFV share of the total light-duty fleet reaches 52.6% under the low ethanol supply case and 62.1% under the high ethanol supply case in 2050. Figure H-29 shows FFV share of new light-duty vehicle sales and FFV share of light-duty vehicle stock. The FFVs reach 50% share of the new light-duty vehicles market in 2038 under the low ethanol supply case and in 2032 under the high ethanol supply case. The 50% share of the light-duty stock is reached in 2048 under the low ethanol supply case and in 2041 under the high ethanol supply case. Thus, a 7–8 year delay is observed for the FFV stock to reach the 50% level. This lag would be different if the rate of change in new FFV sales is modified or new FFV sales during the 2014–2022 period are changed to account for stagnant ethanol production.

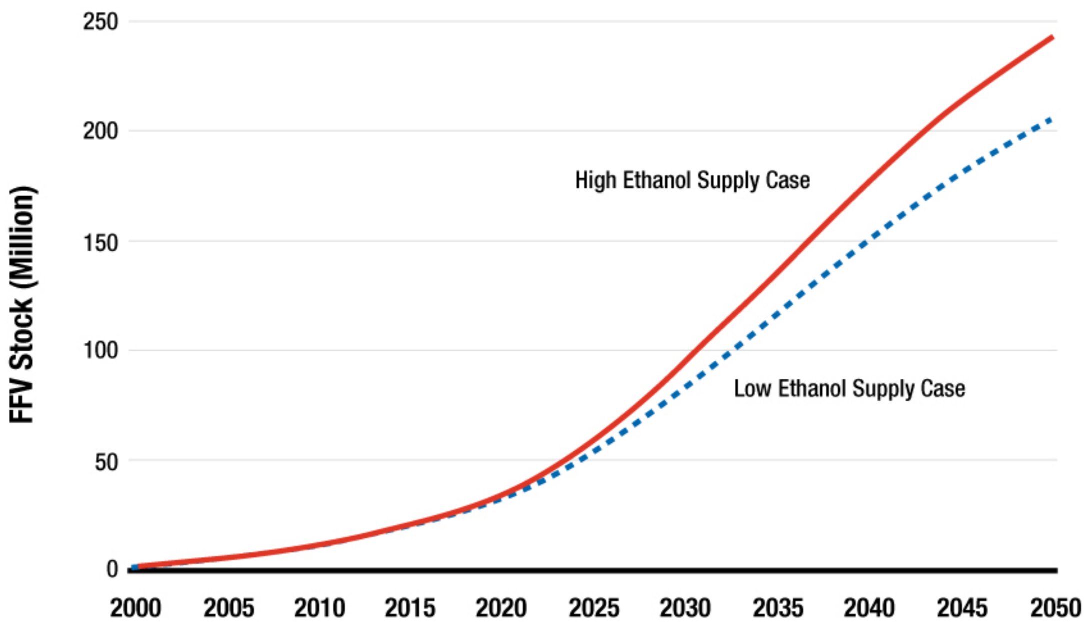


Figure H-28. Number of FFVs on the Road Under the Two Ethanol Supply Cases

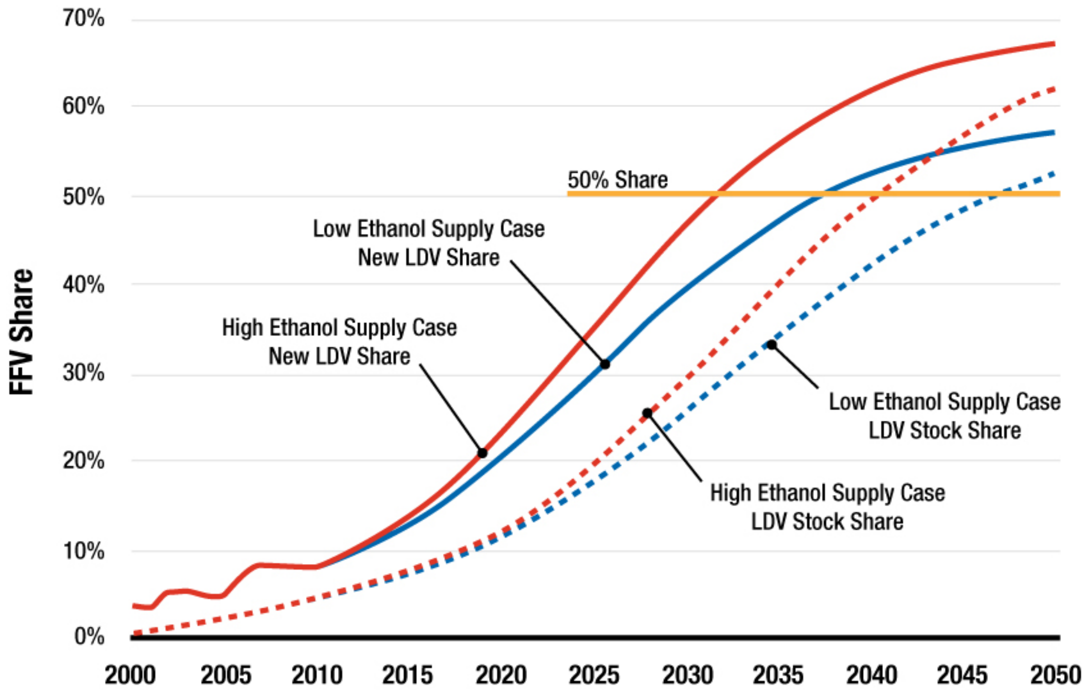


Figure H-29. FFV Share of New and On-the-road Light-duty Vehicles Under the Two Ethanol Supply Cases

H.2.4 Impacts of Ethanol Use by Light-Duty Vehicles

For VISION simulations, the average energy use and GHG emissions of the ethanol types are needed for each given year between 2010 and 2050. The split between corn ethanol and cellulosic ethanol was based on supply estimates from Chapter 2. For the three types of cellulosic ethanol, it was assumed that 30% is produced from forest residues, 35% from agricultural residues, and the remaining 35% from switchgrass.

The simulated ethanol consumption will replace a part of the projected gasoline consumption if no ethanol were produced. Gasoline consumption by light-duty vehicles was estimated under a base case. GREET model estimates of upstream petroleum use for producing gasoline and ethanol were used to estimate total WTW petroleum, or oil, demand under three cases: (1) the base case, (2) the low ethanol supply case, and (3) the high ethanol supply case.

Figure H-30 shows the petroleum energy demand in million barrels per day oil equivalent. Because the two ethanol supply patterns from Chapter 2 are similar through 2022, the incremental impact of the high ethanol supply case is not visible until then. Although the base case oil demand continuously rises, both ethanol supply cases begin to reduce oil demand immediately. Even with increasing ethanol supply, oil consumption continues to increase through 2028 under the low ethanol supply case and through 2025 under the high ethanol supply case. The pattern is then reversed, and oil demand declines. The 2050 oil demand values, under the two ethanol-supply cases, fall below the 2005 oil demand by light-duty vehicles.

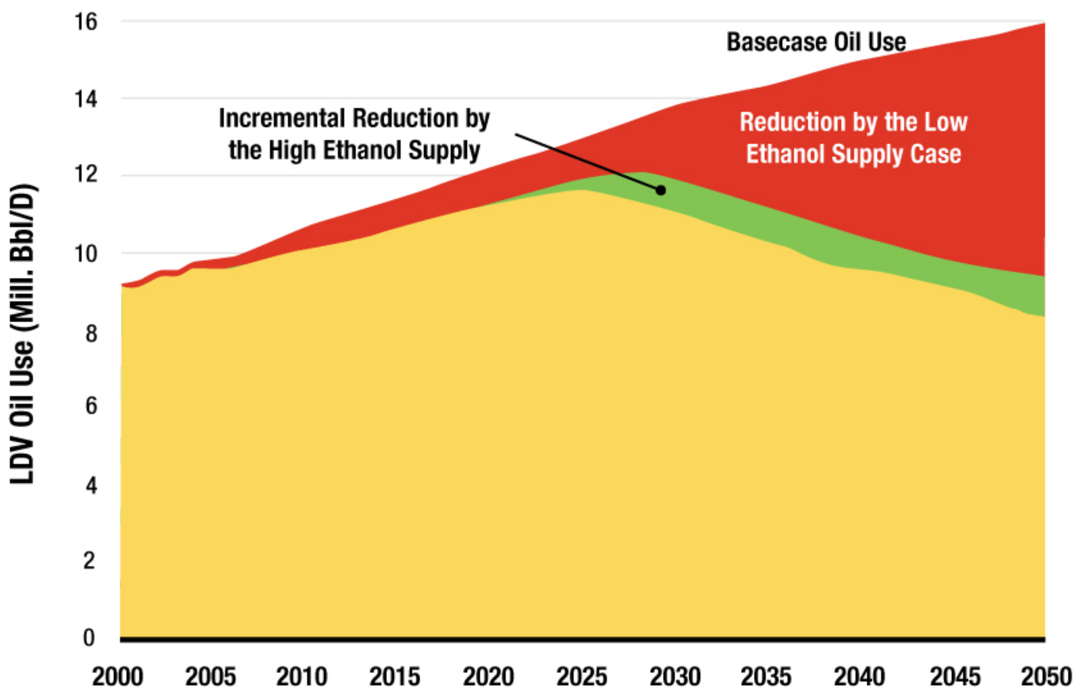


Figure H-30. WTW Oil Use Under the Base and Ethanol Supply Cases

The production of gasoline and ethanol, as well as their use in light-duty vehicles, will generate GHG emissions. The projected gasoline and ethanol demand were used with GREET-generated GHG emissions rates to produce WTW GHG emissions.

Figure H-31 shows WTW GHG emissions under the base, low ethanol supply, and high ethanol supply cases. The WTW GHG emissions show a pattern somewhat different from that of oil use. This is because of the different biomass types (with considerably different GHG profiles) used in ethanol production. The GHG emissions reduction is small through 2022. The GHG reduction is significant after 2022 because of increased ethanol use and greater share of ethanol supply from cellulosic biomass.

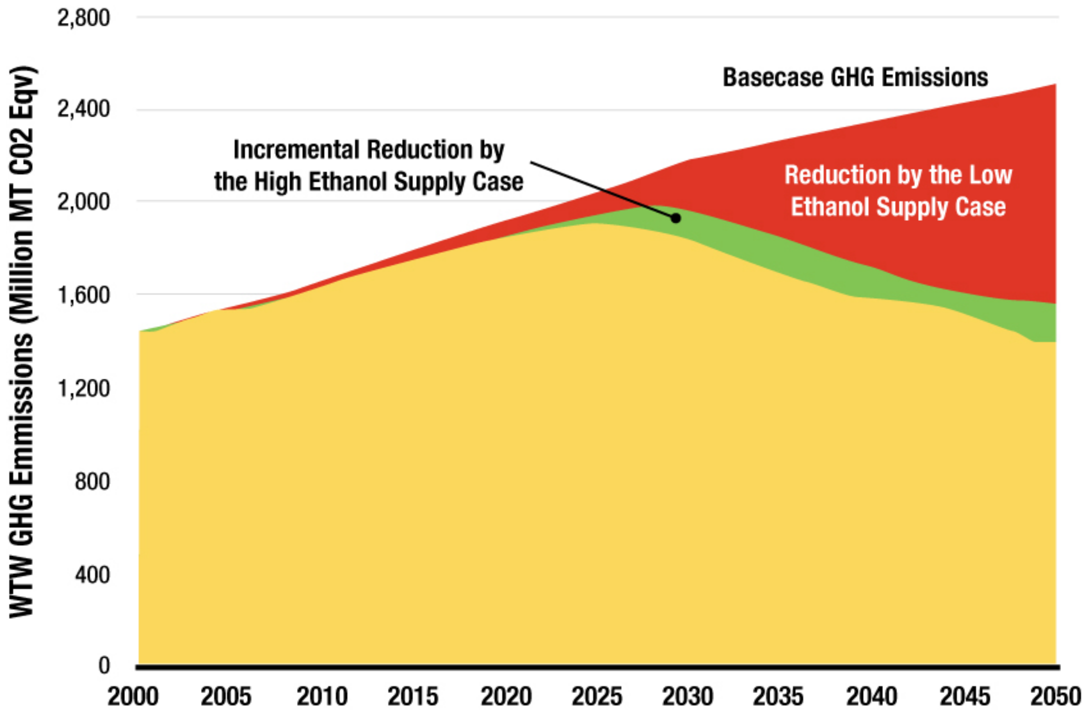


Figure H-31. WTW GHG Emissions Under the Three Cases

Appendix I: Storage, Distribution, Transport, Blending, and Refueling Infrastructure Needs

I.1 Introduction

This appendix addresses the assumptions, calculations, and references for the storage, distribution, and transportation of ethanol. It also addresses the blending, refueling station infrastructure, and vehicle fleet dynamic issues related to the 30 x 30 goal.

The major assumption that underlies all calculations and results in this appendix is the projected annual ethanol production rate. The ethanol production rates used here are based on the availability of biomass as presented in the "Billion Ton" study and conversion technology advances.

The ethanol production curves are based on aggressive and moderate growth scenarios. Each growth curve includes the contribution of ethanol from starch.

- The aggressive scenario reaches 60 billion annual gallons by 2030 and grows to more than 135 billion gallons by 2050. The major assumption behind this curve is that ethanol from cellulosic biomass enters the market early by utilizing fiber and residues.
- The moderate growth curve delays the introduction of ethanol production from cellulosic biomass until 2020 and hits 60 billion gallons in 2045. The corresponding growth rate is not as large as that of the former case.

I.2 Current Practices

Fuel ethanol is used primarily as a gasoline blend. It accounts for slightly less than 3% of the gasoline pool, and typical RFG contains 5%–10% ethanol by volume. Ethanol increases fuel octane and helps users meet gasoline oxygenate requirements in U.S. EPA urban non-attainment areas to improve air quality. Demand for ethanol as a fuel additive has increased sharply as the use of methyl tertiary butyl ether has decreased because of its negative environmental effects. (Methyl tertiary butyl ether was identified as a major aquifer pollutant in 1996 primarily because of leaking underground gasoline tanks.)

Ethanol is currently produced in wet mills and dry mills. Wet mills are typically larger and produce 100 million gallons or more of ethanol per year. Wet mills also produce significant quantities of co-products such as corn oil, corn germ, corn gluten feed, and high-fructose corn syrup. Dry mills are typically smaller. They produce 35–70 million gallons of ethanol annually and the animal feed distillers dried grain.

I.3 Storage

There are two major assumptions used for the storage of ethanol. These assumptions are as stated by Reynolds (Reynolds 2006) and are based on current storage practices for petroleum products.

1. The storage volume required is 10% of the cumulative production rate plus 30% (of the 10%) for inventory receipts and extra working space.

2. The installed cost for storage in conventional tanks is $22.40/barrel.

The cost per gallon of storage for ethanol was calculated without any depreciation. According to the formula from Reynolds, for 60 billion gallons, the storage cost would be $4.16 billion, which equates to $0.07/gallon.

I.4 Distribution

The Midwest has the greatest potential for biomass production and, therefore, the potential to be the largest source of ethanol. Currently, nearly all the ethanol produced from starch is produced in the Midwest.

It is assumed that the pattern of light vehicle transportation fuel distribution shown in Table I-1 will essentially remain the same for this study. Because of this assumption, ethanol use can be compared with finished gasoline use via PADDs (Petroleum Administration Defense Districts) using EIA data.

TableI-1 shows the percentage of 2004 finished motor gasoline consumption by PADD.

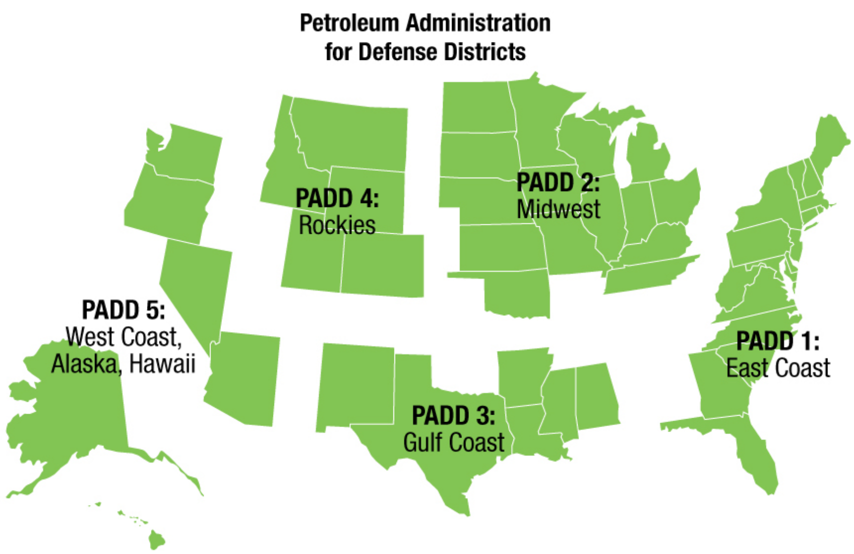


Figure I-1. PADDs

Table I-1. EIA Finished Motor Gasoline Consumption by PADD in 2004

PADD	% Total Gasoline Consumption
1	35.7%
2	28.7%
3	14.8%
4	3.1%
5	17.6%

Tables I-2 and I-3 show biomass resources and ethanol production by PADD. The data in these tables come from POLYSIS, a biomass feedstock database used by Oak Ridge National Laboratory and the USDA.

Table I-2. Cellulosic Biomass Resources by PADD

	2020	2030	2040	2050
PADD 1	14.7%	11.9%	13.6%	12.7%
PADD 2	66.8%	71.3%	69.3%	69.7%
PADD 3	11.3%	10.5%	12.1%	12.9%
PADD 4	2.8%	2.5%	2.2%	2.1%
PADD 5	4.4%	3.8%	2.9%	2.7%

Table I-3. Ethanol Production by PADD*

	Aggressive Scenario (Billion Gallons)				
	2020	**2030**	**2040**	**2050**	**2060**
PADD 1	0.8	5.6	13.7	16.0	15.1
PADD 2	15.7	45.6	81.8	100.8	101.3
PADD 3	0.6	5.0	12.2	16.2	17.0
PADD 4	0.2	1.2	2.2	2.6	2.5
PADD 5	0.3	1.8	3.0	3.3	3.0
Total	**17.6**	**59.2**	**112.8**	**139.0**	**139.0**
	Moderate Scenario (Billion Gallons)				
	2020	**2030**	**2040**	**2050**	**2060**
PADD 1	0.5	4.4	12.4	15.6	15.1
PADD 2	13.2	37.1	74.0	96.1	99.2
PADD 3	0.4	3.9	11.0	15.7	17.0
PADD 4	0.1	0.9	2.0	2.5	2.5
PADD 5	0.2	1.4	2.7	3.2	3.0
Total	**14.4**	**47.7**	**102.0**	**133.1**	**136.9**

These figures assume that all the ethanol from starch comes from PADD 2 (see above).

The distribution pattern is estimated in Figure I-2. The major gathering areas for ethanol in PADD 2 (as indicated by blue stars in the diagram) are Chicago, Des Moines, Minneapolis, and Pierre. Figure I-2 also shows end-user markets.

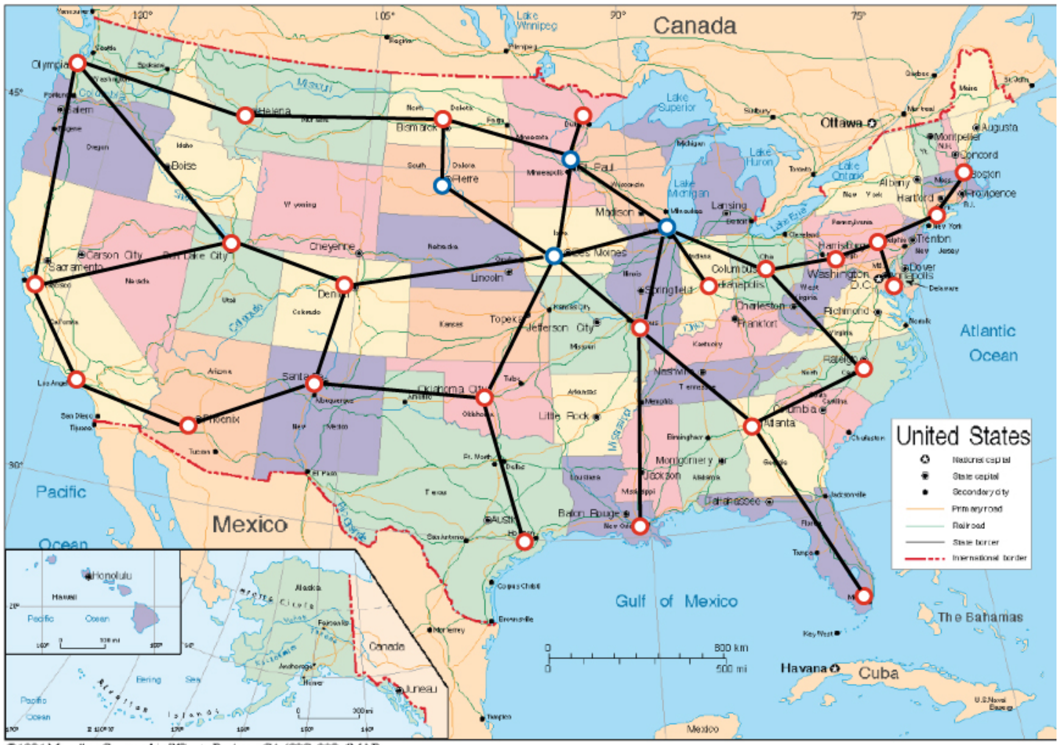


Figure I-2. Sample Ethanol Distribution Map

I.5 Transportation

There are four possible modes of transport to move ethanol from the plant gate to the distribution terminal:

- Truck
- Rail
- Barge
- Pipeline.

Calculations for truck, rail, and barge transportation were taken from Reynolds (Reynolds 2006) and extrapolated to 60 billion gallons from 43 billion gallons. A spreadsheet that accompanied the report calculated the cost of delivering ethanol as a function of distance traveled for truck, rail, and barge. This spreadsheet from Reynolds used MACRS depreciation over a 15-year period (Table I-4, Column 1).

To compare pipeline costs with conventional transportation methods, the same depreciation period was used with projected ethanol production rates over the depreciation period. Table I-4 provides figures for capital payment for pipeline installation.

Table I-4. Installation Costs

Miles of Pipeline 15-Year MACRS Depreciation Period	20,000	30,000	40,000	50,000	60,000	70,000
			Payment (Billion $)			
5.00%	1.0	1.5	2.0	2.5	3.0	3.5
9.50%	1.9	2.9	3.8	4.8	5.7	6.7
8.55%	1.7	2.6	3.4	4.3	5.1	6.0
7.70%	1.5	2.3	3.1	3.9	4.6	5.4
6.93%	1.4	2.1	2.8	3.5	4.2	4.9
6.23%	1.2	1.9	2.5	3.1	3.7	4.4
5.90%	1.2	1.8	2.4	3.0	3.5	4.1
5.90%	1.2	1.8	2.4	3.0	3.5	4.1
5.91%	1.2	1.8	2.4	3.0	3.5	4.1
5.90%	1.2	1.8	2.4	3.0	3.5	4.1
5.91%	1.2	1.8	2.4	3.0	3.5	4.1
5.90%	1.2	1.8	2.4	3.0	3.5	4.1
5.91%	1.2	1.8	2.4	3.0	3.5	4.1
5.90%	1.2	1.8	2.4	3.0	3.5	4.1
5.91%	1.2	1.8	2.4	3.0	3.5	4.1
2.95%	0.6	0.9	1.2	1.5	1.8	2.1

Using Table I-4 and the ethanol production rates in Table I-5, the average cost per gallon was calculated as a function of the cumulative miles of pipeline installed. The graph showing these results is shown in Figure I-3 and also in the body of the report.

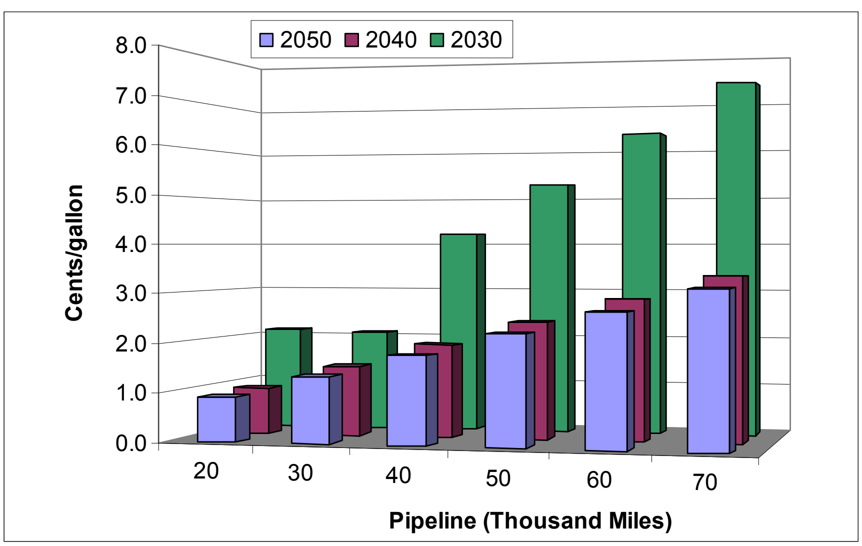


Figure I-3. Ethanol Pipeline Costs

Table I-5. Ethanol Production Rates (Aggressive Scenario)

Year	Billion Gallons	Year	Billion Gallons	Year	Billion Gallons
2030	59.2	2040	112.8	2050	139.0
2031	65.3	2041	115.5	2051	139.0
2032	71.4	2042	118.6	2052	139.0
2033	77.5	2043	122.2	2053	139.0
2034	83.6	2044	127.0	2054	139.0
2035	89.6	2045	131.8	2055	139.0
2036	95.7	2046	136.9	2056	139.0
2037	100.5	2047	139.0	2057	139.0
2038	104.7	2048	139.0	2058	139.0
2039	109.0	2049	139.0	2059	139.0
2040	112.8	2050	139.0	2060	139.0
2041	115.5	2051	139.0	2061	139.0
2042	118.6	2052	139.0	2062	139.0
2043	122.2	2053	139.0	2063	139.0
2044	127.0	2054	139.0	2064	139.0
2045	131.8	2055	139.0	2065	139.0

I.6 Blending

Costs for blending terminals were taken from Reynolds (Reynolds 2006). Reynolds reports that blending equipment at each terminal costs roughly $300,000. Further, adding blending at 600 terminals would cost $180 million. It is assumed that these costs would be the same whether ethanol is blended into gasoline or visa versa.

I.7 Refueling

I.7.1 Vehicle and Retail Refueling Infrastructure to Support E10

Approximately 4 billion gallons of ethanol were used in blends in 2005, and the industry plans to increase production capacity in the near future. In fact, the construction of new ethanol plants and expansion of existing facilities will increase production capacity to more than 6 billion gallons by the end of 2006.

As noted in the main body of the report, expanding ethanol consumption through the widespread use of E10 will have relatively few effects on the existing vehicle and refueling infrastructure and should require no additional capital investment.

There are, however, concerns about ozone-forming emissions from ethanol blended with RFG. When ethanol is blended with gasoline, the fuel's Reid Vapor Pressure (RVP) increases. This leads to an increase in evaporative emissions from the vehicle and during refueling. This can be controlled by reducing the RVP of the gasoline blend stock. This is already done for reformulated gasoline (RFG) in geographic areas that use ethanol and are in non-attainment with EPA air quality requirements for ozone (see Figure I-2). In areas that are in non-attainment for carbon monoxide (CO) only , the EPA generally grants a waiver for RVP requirements to allow the use of ethanol as an oxygenate to reduce carbon monoxide emissions in winter months.

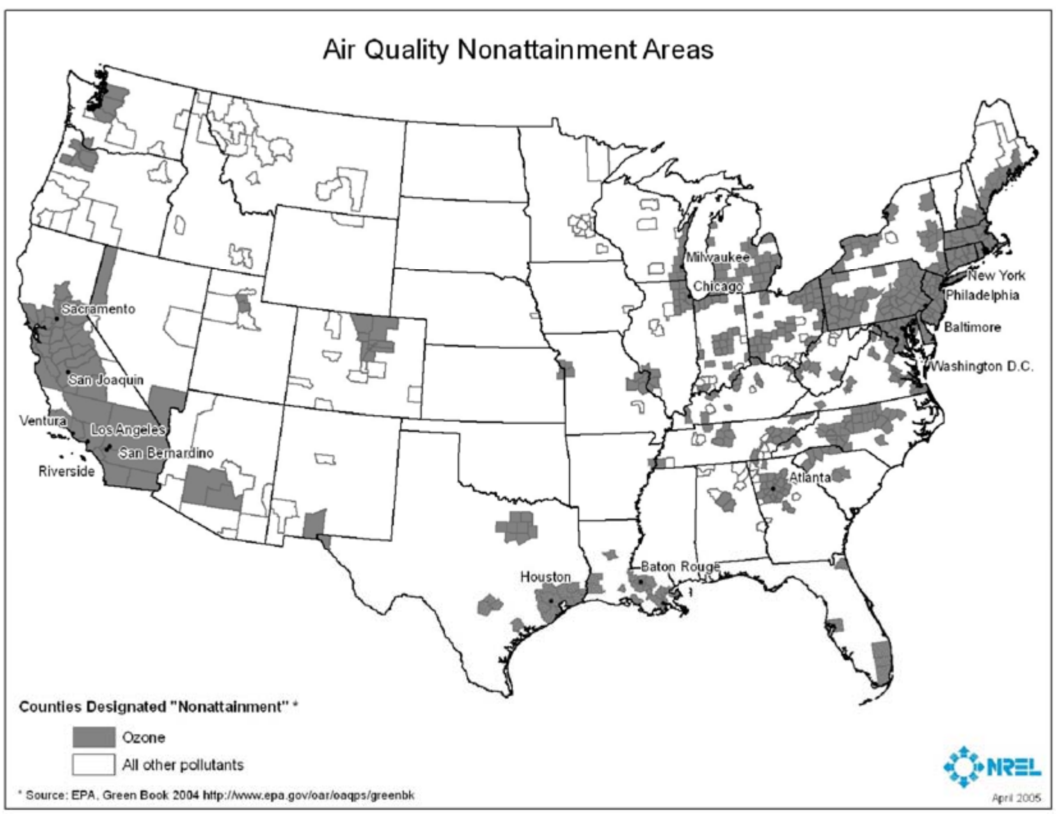


Figure I-4. Air Quality Non-attainment Areas That Could Affect E10 Deployment

Recent studies conducted by the Coordinating Research Council indicate, however, that there may be ethanol-related increases in VOC emissions independent of RVP because of permeation through rubber and plastics on today's conventional vehicles (Inside Fuels 2006). This requires further study, and indications are that today's FFVs do not have this problem.

If ethanol were excluded from RFG because of the permeation emission concern, the potential market for blends would be reduced by 30% (the percentage of RFG in the gasoline pool) to a little more than 10 billion gallons annually by 2015. Figure I-3 shows this change. Both cases—one with and one without ethanol in RFG—achieve the 60-billion-gallon goal in 2030. Assuming there is no ethanol in RFG while achieving the goal in 2030 has two effects:

1. It reduces the amount of ethanol used in blends while increasing the amount of ethanol used in E85.
2. It reduces the total amount of ethanol in the earlier years.

There is also uncertainty regarding the impact of ethanol on tail-pipe emissions of NO_x and aldehydes. This is mainly an issue for modern FFVs, state regulatory agencies are also concerned about the impact of E10. While some studies show little or no effect on these emissions, other studies suggest that increases might be significant. Very little emission test data are available for recent technology vehicles, and in addition, most available test data are for ethanol blended with gasoline that is not representative of that actually being used. Additional testing is warranted to alleviate the concerns of air quality regulators.

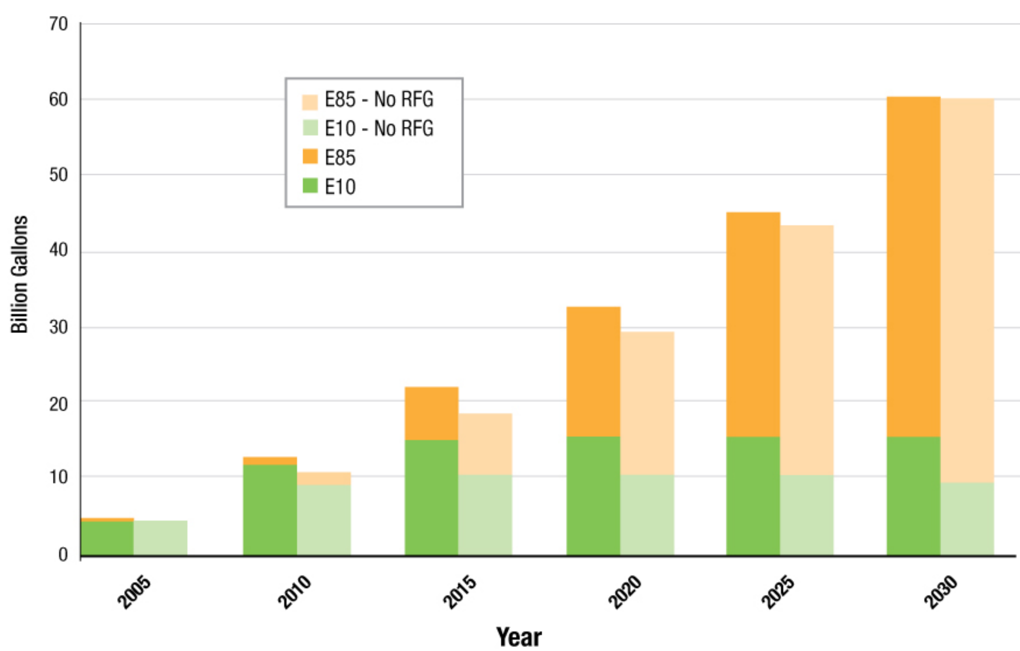


Figure I-5. Effect of Excluding Ethanol in RFG on Projected Ethanol Use

I.7.2 Vehicle and Retail Refueling Infrastructure to Support E85

Increasing the use of ethanol via E85 involves a different set of hurdles. These hurdles include the availability of FFVs and the ability of drivers to select E85 rather than gasoline based on convenience, price, and performance.

I.7.2.1 Retail E85 Refueling Infrastructure

In the United States today, roughly 169,000 retail outlets (National Petroleum News 2005) sell more than 380 million gallons of gasoline each day (EIA 2006b). This means that the average retail gasoline station sells 828,000 gallons annually. In contrast, only 619 (DOE 2006a) stations dispense E85. To increase the sale of E85 beyond the roughly 31 million gallons sold in 2004, the number of E85 refueling stations must greatly increase so drivers are not inconvenienced.

The percentage of retail refueling stations that must sell E85 to be convenient for FFV drivers is not known. However, if a driver could count on every other station in an area to sell E85, it should be reasonably convenient. To reach 50% E85 station coverage nationwide, 84,000 more stations must be equipped to dispense E85. However, targeting specific regions for E85 use would reduce the required number. This strategy can also have other advantages related to the cost of E85 at the pump.

Figure I-4 shows the five U.S. PADDS. Figure I-5 shows the most likely areas of biomass feedstock availability. A comparison of these maps shows that the heaviest concentrations of biomass feedstocks are in the Midwest, South, and Northeast regions. Targeting the sale of E85 and FFVs in these three regions would place ethanol end markets nearest its feedstocks. Because feedstock transportation is expensive, ethanol production facilities will be located in these areas to minimize costs. In addition, the proximity of end markets to production facilities will minimize the cost of distributing ethanol to the end markets.

Targeting the central, South, and Northeast regions for E85 use also takes advantage of existing E85 infrastructure. These regions have the bulk of current ethanol production and E85 refueling stations, and their drivers are more familiar with E85. In fact, there are 580 E85 stations in the targeted regions. These represent 94% of the current E85 retail infrastructure.

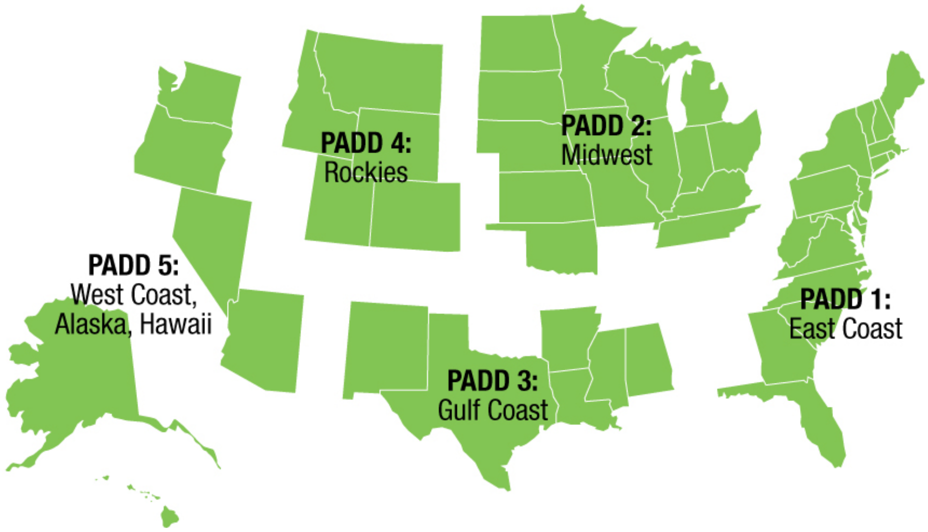


Figure I-6. PADDs

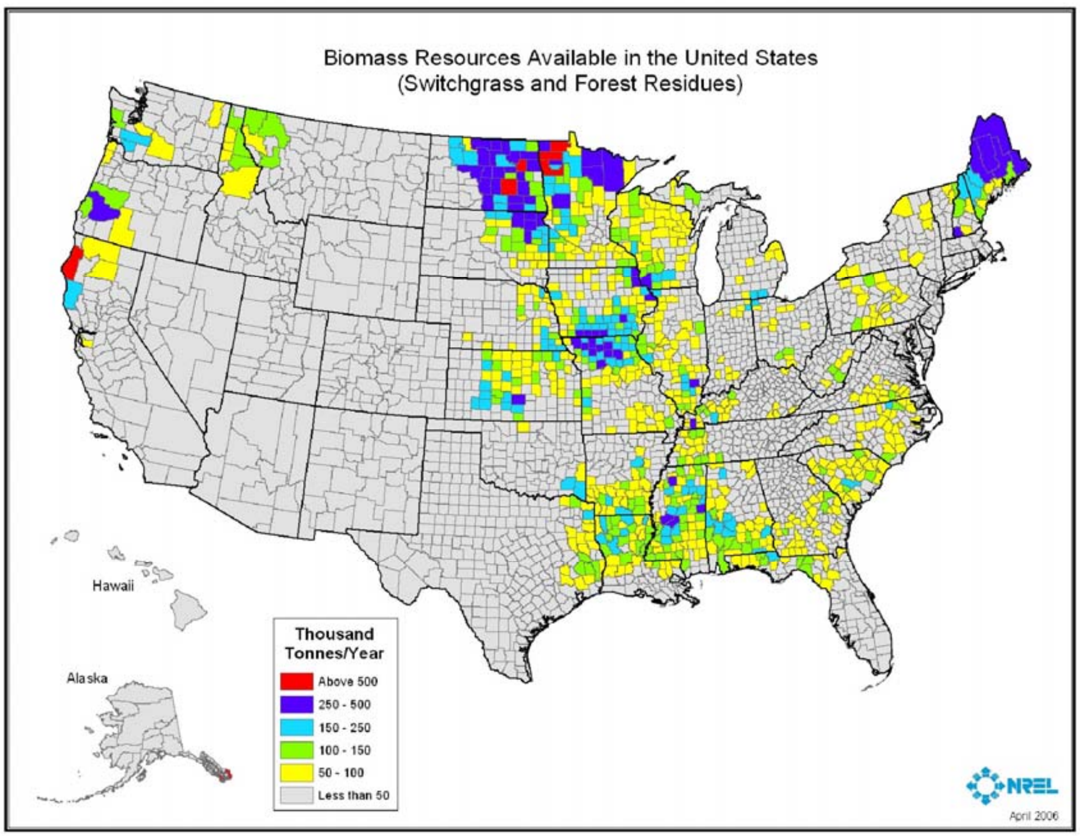


Figure I-7. Switchgrass and Forest Residue Resources for Ethanol

Figure I-6 shows projections for the growth of E85 stations and E85 use in the three-region area through 2030. An E85 station growth rate of 2% per year was assumed from 2008 to 2030. Based on the number of E85 stations and the total volume of E85 sold, the average station in 2030 would sell 842,000 gallons of E85. This is considerably more than the average

E85 sales per station of roughly 95,000 gallons in 2005, but it is close to the 828,000 gallons of gasoline sold by the average station in 2005.

It was assumed that the number of stations will remain roughly constant over time while station throughput will increase based on two countervailing trends:

1. The number of stations has contracted in recent years (195,455 in 1995 to 168,987 in 2005) as stations have moved to higher-volume pump dispensers (National Petroleum News 2005).
2. Annual sales of gasoline are projected by the EIA to increase from 2005's 138 million gallons to 185 million gallons in 2030.

If these trends bear out, then an average refueling station will dispense approximately 1.1 million gallons in 2030.

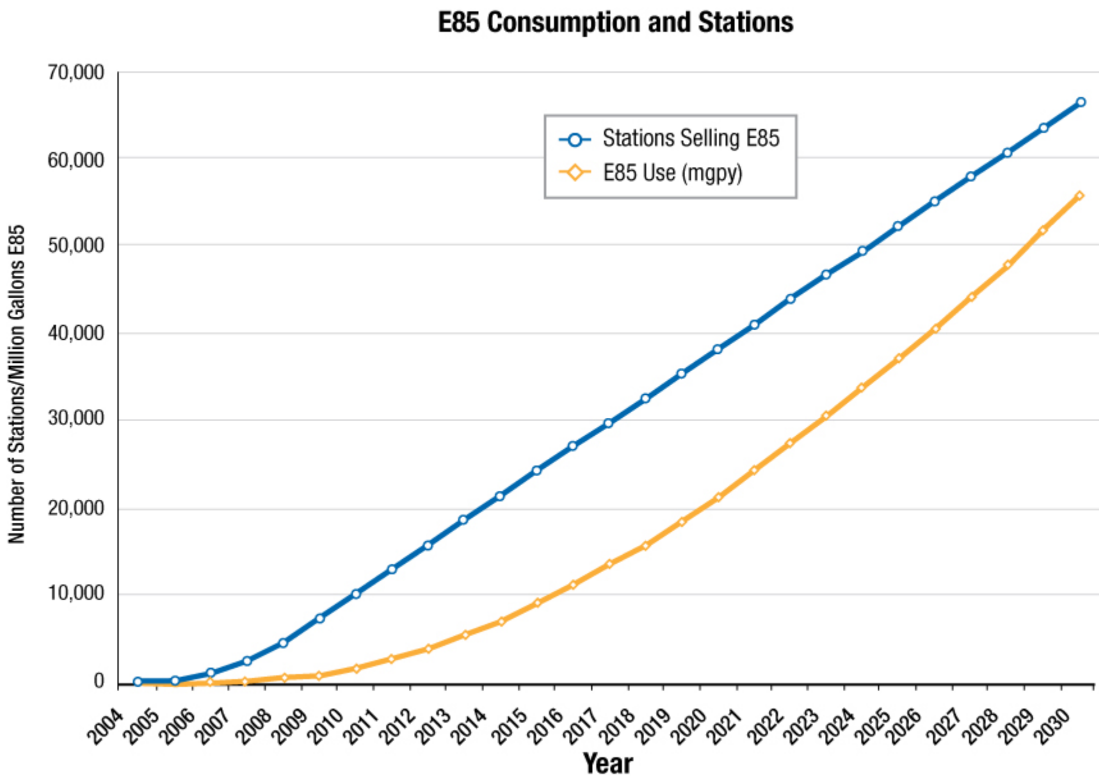


Figure I-8. Projections for Growth in E85 Stations and E85 Consumption

The effect of E85 on gasoline sales in the three-region area will be significant. Projecting 78% of national fuel use in 2001 to 2030 shows that the three-region fuel market in 2030 will be the equivalent of 146 billion gallons of gasoline. (See Figure I-7 for a breakdown by division). The projected 2030 use of ethanol in E85 in these regions is 45 billion gallons; this would displace 20.5% of the regions' 146 billion gallons of gasoline.

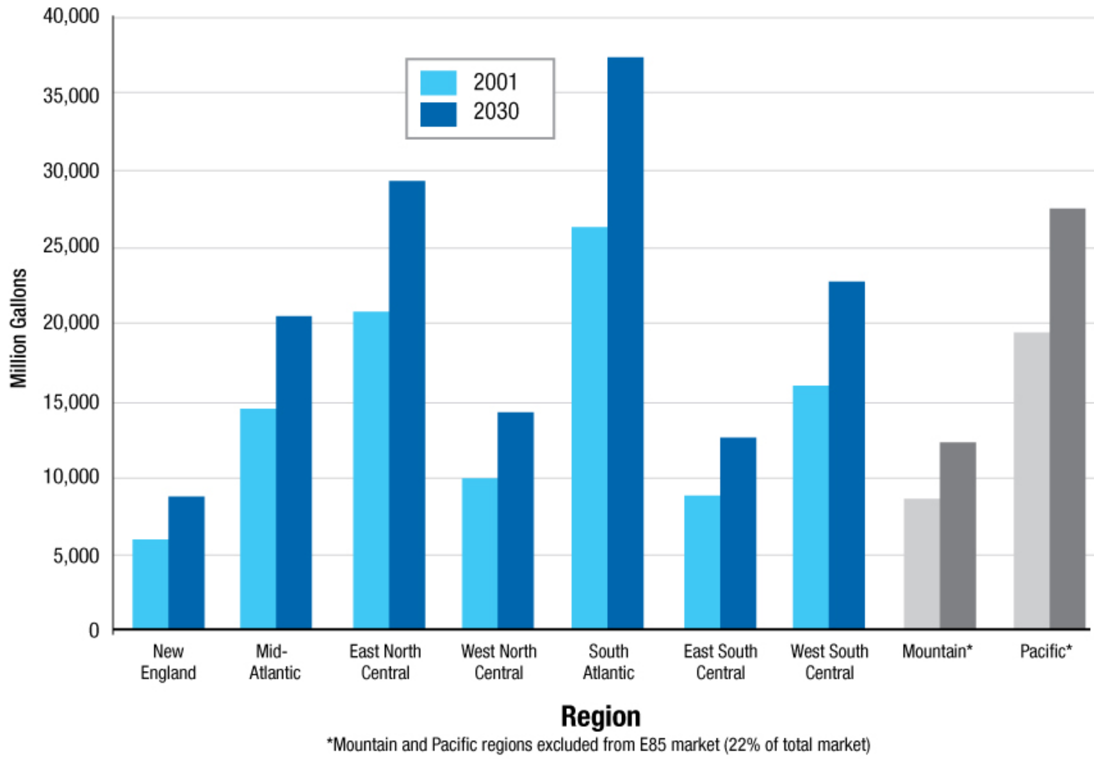


Figure I-9. Gasoline Consumption by Census Division

Converting an existing gasoline pump to be compatible with E85 requires nominal changes.

- Storage tanks
  Most metal underground storage tanks that meet U.S. EPA December 1998 codes can store E85. Double-walled fiberglass tanks are generally compatible as well, but single-walled tanks installed before 1992 may not be compatible. However, a few are in use today. Compatible storage tanks will need to be cleaned, at a cost of roughly $2,000/tank.
- Dispensing pumps
  Because ethanol is highly corrosive, E85 pumps must be equipped with a non-aluminum (i.e., nickel-plated or steel) nozzle, compatible breakaways, and a Teflon-lined hose with stainless steel ends and fittings. Pumps and dispensing equipment are highly variable and depend on the performance and safety features selected.
- Installation costs
  Permitting, planning, and electrical and mechanical installation are important parts of the conversion process.

Table I-1 shows a sample of nine bids for refueling station retrofits as reported to the Alternative Fuels Data Center at NREL. Because each station owner decides the quality and features of station equipment, the costs vary significantly. The data in Table I-1 indicate that the average cost to convert a station (generally one dispenser with two nozzles) is $24,690. To satisfy demand, stations would require about two dispensers/four nozzles per station to meet

2030 demand for E85. Therefore, the conversion of 60,000 stations in the targeted regions would cost roughly $3 billion.

Table I-4. Sample of E85 Refueling Station Retrofits

Bid Number	Number of Tanks	Above or Below Ground	Tank Cost	Number of Dispensers	Dispensing Cost	Labor	Total Cost
1	0		N/A	1	$3,000	$3,965	$15,231
2	1	Below	$8,872	0	$0	N/A	$27,218
3	1	Below	$2,825	1	$4,970	N/A	$20,196
4	1	Below	$3,961	1	$5,500	$12,365	$27,321
5	2	Below	N/A	2		N/A	$57,922
6	0		N/A	1	$11,223	$1,078	$4,118
7	1	Above	$8,704	1	$2,957	$12,000	$32,574
8	1	Below	$3,340	1	$2,130	$3,000	$13,525
9	1	Below	$4,662	1	$4,404	$6,000	$24,105
Average Costs			**$5,394**		**$4,273**	**$6,401**	**$24,690**

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NREL report assessing market drivers and technology needs required to supply 30% of 2004 motor gasoline demand with biofuels by 2030. Goal will require a 60 billion gallon/year ethanol industry by 2030 and necessitates a target price of $1.07/gallon ethanol by 2012. Report discusses meeting those targets through biochemical and thermochemical conversion technologies.

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