GROWING ENERGY

How Biofuels Can Help End America's Oil Dependence

Principal Author
Nathanael Greene, NRDC

Contributing Authors
Fuat E. Celik, Princeton University
Bruce Dale, Michigan State University
Michael Jackson, NRDC
Kemantha Jayawardhana, Dartmouth College
Haiming Jin, Dartmouth College
Eric D. Larson, Princeton University
Mark Laser, Dartmouth College
Lee Lynd, Dartmouth College
Don MacKenzie, Union of Concerned Scientists
Jason Mark, Union of Concerned Scientists
John McBride, Dartmouth College
Samuel McLaughlin, Oak Ridge National Laboratory
Daniel Saccardi, NRDC

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ABOUT NRDC

The Natural Resources Defense Council is a national nonprofit environmental organization with more than 550,000 members. Since 1970, our lawyers, scientists, and other environmental specialists have been working to protect the world's natural resources and improve the quality of the human environment. NRDC has offices in New York City; Washington, D.C.; Los Angeles; and San Francisco.

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EXECUTIVE SUMMARY

America's oil dependence threatens our national security, economy, and environment. We consume 25 percent of the world's total oil production, but we have 3 percent of its known reserves. We spend tens of billions of dollars each year to import oil from some of the most unstable regions of the world. This costly habit endangers our health: America's cars, trucks, and buses account for 27 percent of U.S. global warming pollution, as well as soot and smog that damage human lungs.

The United States does not have to rely on oil to drive our economy and quality of life. We can replace much of our oil with biofuels—fuels made from plant materials grown by American farmers. These fuels, especially those known as cellulosic biofuels, can be cost-competitive with gasoline and diesel, and allow us to invest our energy dollars at home. They can also slash global warming emissions, improve air quality, reduce soil erosion, and expand wildlife habitat.

If we follow an aggressive plan to develop cellulosic biofuels between now and 2015, America could produce the equivalent of nearly 7.9 million barrels of oil per day by 2050. That is equal to more than 50 percent of our current total oil use in the transportation sector and more than three times as much as we import from the Persian Gulf alone.

In combination with improved fuel efficiency in cars and smart growth planning in our towns and cities, biofuels can free America from foreign oil in a cost-effective and environmentally safe way:

- By 2025, producing the crops to make these fuels could provide farmers with profits of more than $5 billion per year.
- Biofuels could be cheaper than gasoline and diesel, saving us about $20 billion per year on fuel costs by 2050.
- Biofuels could reduce our greenhouse gas emissions by 1.7 billion tons per year—equal to more than 80 percent of transportation-related emissions and 22 percent of total emissions in 2002.

THE ECONOMIC AND ENVIRONMENTAL BENEFITS OF BIOFUELS

This report offers a concrete plan for realizing these security, economic, and environmental benefits of biofuels. The report is based on two years of cutting-edge, original analysis by a diverse group of agricultural, engineering, and environmental experts who have worked together to evaluate the sustainable potential for biofuels. This analysis is the first to assess the cumulative impact of a range of innovations in the context of a broad effort to reduce our oil dependency. We find more cost-effective potential than do previous studies largely because we focus on what bioenergy technologies will be able to do when they are commercially mature and operating on a large scale. We also find land is less of a constraint because we focus on integrating growing biomass and current agricultural products.

Our key findings include:

Biofuels can be competitive with gasoline and diesel. Advanced biofuels production facilities could produce gasoline alternatives at costs equal to between \$0.59 and \$0.91 per gallon of gasoline by around 2015. Diesel alternatives could cost the equivalent of \$0.86 per gallon of diesel. These prices are competitive with average wholesale prices over the last four years—\$0.91 per gallon for gasoline and \$0.85 per gallon for diesel.

Biofuels will provide a major new source of revenue for farmers. At \$40 per dry ton (the price assumed for the biofuels costs above), farmers growing 200 million tons of biomass in 2025 would make a profit of \$5.1 billion per year. This is less than one-sixth the total amount of biomass we have found farmers could produce by 2050. A market for cellulosic biomass will benefit all farmers by, among other things, proving a demand for their residues and broadening the range of crops they can grow.

We have enough land for biofuels to make a big contribution. Even under an aggressive growth scenario for the biofuels industry, land does not become a constraint until the mid-21st century, and we believe that farmers will find ways to meet traditional agricultural demands and energy demands on our existing croplands well beyond then. Our study shows that farmers could also produce animal feed protein at the same time they generate biofuels, enabling the land currently used to grow protein to also grow energy crops.

The model energy crop considered, switchgrass, offers major environmental benefits. The yield of switchgrass—a native, perennial prairie grass—can be more than doubled over time, reducing the land required to produce a given amount of biofuels. Switchgrass also offers low nitrogen runoff, very low erosion, and increased soil carbon—which is actually enhanced when the crop is harvested. Switchgrass also provides good wildlife habitat. It is likely that such benefits are not limited to switchgrass, although other crops were not investigated in any detail.

Biofuels can provide major air quality benefits. In addition to avoiding more than a ton of greenhouse gas emissions for every ton of biomass used to make biofuels, biofuels contain no sulfur and produce low carbon monoxide, particulate, and toxic emissions. As a result, achieving air pollution emissions reduction targets is expected to be somewhat easier using biofuels than using petroleum based fuels.

Concerns over low-percentage blends of ethanol in the existing fleet can be addressed. Low-percentage blends of biofuels in gasoline are controversial because they can result in increased nitrogen oxide and volatile organic compound emissions, both of which contribute to urban smog. The newest vehicles, however, can largely eliminate these impacts—making air quality concerns a transitory problem. With appropriate regulatory safeguards and carefully crafted policies, these impacts can be kept to acceptable levels during an aggressive push toward a clean biofuels future.

RECOMMENDATIONS FOR MAKING BIOFUELS AFFORDABLE AND SUSTAINABLE

To realize these benefits, we need to make a commitment to biofuels today. If we start an aggressive push to develop and deploy biofuels in the next year or two, by 2015 we could produce our first billion gallons of cellulosic biofuels at costs approaching those of gasoline and diesel. If done in a focused and consistent manner, this commitment should not cost more than $2 billion. Three key steps are needed to make this happen:

Invest in a package of research, development, and demonstration. An investment of about $1.1 billion between 2006 and 2015 in applied fundamentals, innovation, and demonstration will make biofuels affordable for American consumers. The funds should target the best ways to process cellulosic biomass, create multiple products at the same time as generating biofuels, and improve feedstock production.

Fund deployment policies to drive the deployment of the first billion gallons of cellulosic biofuels. The federal government should make sure the first billion gallons of production get built by 2015 by making available about $900 million in incentives. These incentives should rely on the private sector's due-diligence process to decide which projects get built. The government should also encourage the use of production incentives whenever possible, and leave the industry self-sufficient by phasing out subsidies as the industry grows.

Adopt a renewable fuels standard for cars and trucks. Adopting a renewable fuels standard would provide the steady pressure needed to start breaking our oil dependence. This standard should offer incentives for environmental performance and include safeguards for air and water quality as the use of ethanol increases. We also recommend requiring that all vehicles sold by 2015 be able to use both traditional fuels and biofuels.

A THREE-PART STRATEGY FOR SLASHING AMERICA'S OIL DEPENDENCE

While biofuels can play a central role in breaking our addiction to oil, under business as usual in 2050 we could easily be using over 30 million barrels of oil per day. Even with biofuels reducing this by nearly 8 million barrels per day, we would still be extremely vulnerable to the volatility of oil prices, the energy security risks of being so dependent on oil, and the environmental impacts of oil.

Biofuels will not work in isolation. If we are serious about reducing our dependency on oil, we must do it through a combination of new sustainable fuel production, fuel efficiency, and smart growth. This report focuses on biofuels and shows how fuel efficiency and smart growth can make the sustainable contribution of biofuels much more significant. However, the importance of a package approach is a common feature of all paths to a sustainable transportation sector, including hydrogen and electric vehicles.

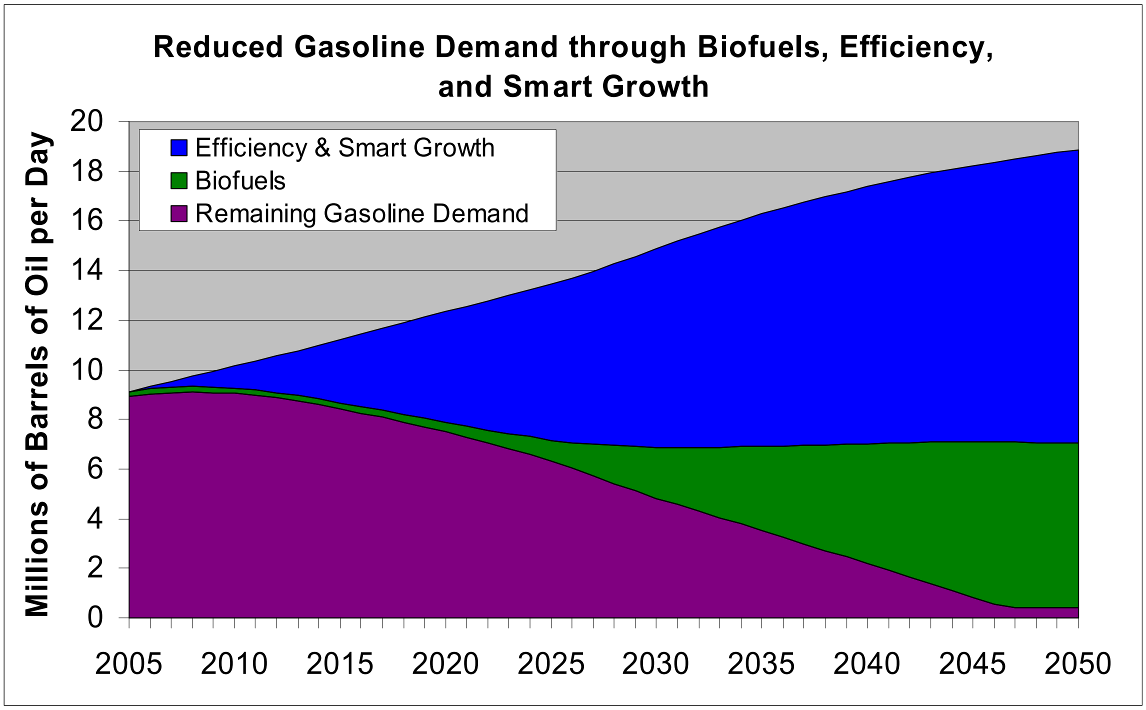


Figure ES 1. Virtually Eliminating Gasoline Demand by 2050.

Combined, biofuels, efficiency, and smart growth can reduce our transportation-related oil demand by two-thirds, from more than 30 million barrels of oil per day to about 10 million barrels. In this context, biofuels would provide more than 40 percent of our remaining transportation-related energy needs and virtually eliminate our demand for gasoline.

If we want to produce an alternative to oil that is truly good for the whole country, we must make fair treatment of farmers and the environment as central to our policies as producing cost-effective biofuels. A collaborative effort between these two communities is crucial to not only enacting these policies but capturing their full benefits. And the first steps in establishing such a collaborative must be for each community to recognize the central issues and concerns of the other and for each community to commit to addressing these concerns. We hope that this report, in addition to providing a vision of a biofuels future, will help in the formation of such an agricultural-environmental collaborative.

By focusing on innovation and change, this study takes a different approach from any before it, and as a result, we have identified sustainable and cost-effective ways for biofuels to play a central role in dramatically reducing the oil dependency of our transportation sector. Potential on this scale deserves an effort at least as large and focused as the one we have proposed. The key to delivering on the promise of biofuels is to start now.

CHAPTER 1

THE CASE FOR AN AGGRESSIVE PUSH ON BIOFUELS

Energy from biomass and particularly fuels from biomass can provide tremendous economic, environmental, and energy security benefits. As energy prices rise and become increasingly volatile, and as evidence of global warming mounts, the case for clean, renewable, domestic sources of energy has never been clearer.

Biomass—basically plant matter—can be converted into heat, electricity, and alternatives to gasoline and diesel. The bioenergy that results can be a clean, renewable domestic alternative to fossil fuels. The United States uses more bioenergy than any other source of renewable energy except for hydro, and we've only just begun to tap the potential of bioenergy.

The potential benefits of increasing our use of bioenergy can be grouped into three categories. Bioenergy can improve our economy, especially in the agricultural sector, our environment, especially in terms of global warming, and our energy security. The analysis in this report finds that using biomass to make electricity (also known as biopower) can provide roughly the same economic and environmental benefits as making fuels (also known as biofuels), but when energy security is considered, the balance of benefits tips strongly in favor of using biomass to help reduce our oil consumption by producing biofuels. Our near total reliance on petroleum to fuel transportation threatens our economy and environment, but it poses a unique threat to our energy security.

- With only 5 percent of the world's population and 2 percent of the world's reserves of oil, the United States consumes 25 percent of the world's oil.[1]
- We use 70 percent of the oil we consume in the transportation sector, and within the transportation sector we get 97 percent of our energy from oil.[2]
- We import the majority of our oil. Our dependence on imported oils only likely to grow—and with it our dependence on unstable parts of the world like the Middle East, Nigeria, Venezuela, and Russia.
- The price spikes that have accompanied terrorist attacks and regional unrest also show that our energy security directly impacts our economic security.

Our addiction to oil also imposes an environmental cost. The burning of gasoline and diesel releases polluting emissions that cause acid rain, smog, and cancer-causing soot, contributing to thousands of premature deaths in the United States every year.[3]

Furthermore, the transportation sector is responsible for 27 percent of total U.S. greenhouse gas emissions.[4] Carbon dioxide is the primary global warming pollutant.

Given the finite supply of oil, the United States will ultimately make a transition away from this fuel; it is just a matter of when this will happen and how much disruption the transition will bring with it. There are demand-side solutions—using petroleum more efficiently—and supply-side solutions—finding sustainable alternative fuels—and we need to be pursuing both. The choice facing the United States today is whether we will wait for a crisis to strike and risk global instability, economic depression, and environmental devastation, or whether we will start today on a smooth transition to improved energy efficiency and the fuels of the future.

BIOFUELS CAN FUEL THE FUTURE

Based on a unique analysis presented in the next chapter, we find that biofuels coupled with vehicle efficiency and smart growth could reduce the oil dependency of our transportation sector by two-thirds by 2050 in a sustainable way. This would require a dramatically larger and more focused effort than we are currently devoting to bioenergy, but sustainable potential on the scale found in this study clearly justifies such an effort.

This report is based on two years of analysis by a diverse group of agricultural, engineering, and environmental experts who have worked together to evaluate the sustainable potential for biofuels. Our analysis is built on detailed engineering and economic analyses of what bioenergy technologies will be able to do when they are commercially mature and operating on a large scale. This analysis is the first to assess the cumulative impact of a range of innovations in the context of a broad effort to reduce our oil dependency. The assessment of mature technologies allows deeper insight into the performance of individual technologies and fair comparisons between them. Our study is premised on the belief that all paths to a sustainable transportation sector require a combination of alternatives to oil and increased fuel efficiency. Therefore, we have assessed biofuels potential in the context of an aggressive effort that includes improving vehicle efficiency and reducing vehicle miles traveled through smart growth policies.

We also consider changes in the agricultural sector. We assume that if farmers saw profits providing biomass for energy, they would innovate and change and find ways to get more out of the land. This includes switching to crops that can meet multiple needs and improving the yield of crops so that they can get more from each acre. However, to ensure that the potential we have identified is sustainable, we have limited our analysis to land that is already currently managed for crops, required that the innovation and changes we consider maintain or improve the environmental performance of the agricultural sector, and assumed that we must continue to meet all the demands currently met from our croplands.

Our analysis focuses on the use of cellulosic biomass—the leaves, stems, and stalks of plants as opposed to the fruit and seeds (e.g. corn kernels, wheat, soybeans, rapeseed). In particular, we have focused on switchgrass because it has many desirable environmental qualities, shows great promise for increased yields, can be grown in geographically diverse regions, and can be used to meet a range of needs simultaneously. However, we do not mean to imply that switchgrass is the only, or necessarily the best, cellulosic feedstock. While we discuss the benefits of switchgrass in the next chapter, we have not conducted a comparative analysis of other sources of cellulosic biomass.

Our analysis was performed along three prongs. First we identified a range of technology innovations and forecast their performance once they reach maturity. From this, we chose the package of technologies that appears to offer the most promise in terms of displacing oil and reducing greenhouse gas emissions at prices that are competitive with gasoline and diesel. We used this package to assess the long-term potential on existing croplands. Finally we laid out a package of policies needed to enable the full range of innovations we have considered and to make biofuels a competitive and sustainable reality.

There are many potential benefits from a renewable, domestically produced alternative to fossil fuels. Biomass, managed right, can provide all of them. Based on the results presented in this report, we believe that using biomass primarily, but not exclusively, to produce alternatives to gasoline and diesel will maximize these benefits. Biopower and biofuels both reduce a similar amount of global warming pollution per ton of biomass used. We find that biofuels are likely to be more cost-competitive with gasoline and diesel than biopower will be with traditional electricity, but there is a lot of volatility in the price of oil and electricity, and that could change this conclusion.

The strongest argument for using biomass to make biofuels is that only biofuels can help reduce our dependency on oil. As discussed earlier, the transportation sector is essentially completely dependent on oil, and this dependency ties us through the international oil market to an extremely volatile market and extremely insecure parts of the world.

Fortunately, while we focus on reducing oil dependency in the context of sustainability, it is not an all-or-nothing choice. The process of making biofuels allows for the simultaneous production of a range of products including power, and the policies we recommend in Chapter 2 will advance both biofuels and biopower technologies.

We conclude that with an aggressive research, development, demonstration, and deployment program costing about $2 billion through 2015, we estimate that by 2050 biofuels could contribute the equivalent of 7.9 million barrels of oil per day (53 percent of our current oil demand for the transportation sector), and virtually eliminate our demand for gasoline. Furthermore, biorefineries being built in the second half of the next decade could produce biofuels at a cost competitive with wholesale gasoline and diesel. Combined with efficiency and smart growth, biofuels could reduce our oil consumption for transportation by 68 percent in 2050.

Developing this much biofuel would result in a dramatic reinvestment in our agricultural sector. Farmers would provide the lifeblood for our transportation system, as well as for our dining tables. Just as important as our findings on oil displacement, we believe that we can indeed produce this much biofuel without increasing the amount of land devoted to agriculture and while still meeting all our food, animal feed, and textile needs.

Biomass energy is but one of several long-term options for renewable power and fuels. While this analysis does not evaluate other strategies, our findings suggest that biofuels offer a very attractive opportunity for addressing the environmental impacts of transportation. Many policy makers believe that biofuels as a whole will never contribute more than about 10 percent of our transportation energy needs and will always be expensive. Bringing together innovation and change, this study takes a different approach than any before it, and as a result, we have identified a sustainable and cost-effective way to dramatically reduce the oil dependency of our transportation sector. Potential on this scale deserves an effort at least as large and focused as the one we have proposed. The key to delivering on the promise of biofuels is to start now.

BIOFUELS CAN PROVIDE FARMERS WITH A NEW SOURCE OF INCOME

To displace 7.9 million barrels of oil in 2050, we will need to use more than 1.3 billion tons of cellulosic biomass each year. This will create a major new market for farmers and potentially relieve the downward price pressures created by the fact that our productive agricultural capacity is greater than our demand. We currently spend well over $151 billion annually on oil, with over 60 percent of this going overseas, more than $24 billion to the Persian Gulf alone.[5] Biofuels that are cost-competitive with gasoline and diesel will allow us to invest our energy dollars at home. And if done carefully, biofuels should dramatically reduce global warming pollution and maintain or improve air, water, soil, and habitat quality across our country.

A new market for cellulosic biomass has the potential to dramatically change the agricultural sector, but these changes will happen only over time. Meanwhile, there are significant supplies of low-cost agricultural residues with high cellulose and hemicellulose content including corn fiber, corn stover, sugar cane fiber, rice hull, and wheat straw. The first cellulosic biofuels facilities are likely to take advantage of these low-cost feedstocks. As residues such as these become valuable, farmers located near cellulosic biofuel plants will have a new potential revenue stream.

Over time, though, we believe that farmers will respond to this new market by finding ways to get more from the land, using innovations to integrate the new demand for cellulose into the existing demand for agricultural products. This integration will be driven by the economics of the marketplace. If farmers can sell different parts of the same plant to different markets, they can increase their revenues and diversify their risk. We believe that integration innovations will allow us to produce nearly 165 billion gallons of biofuels by 2050 just from land that is already under cultivation while still meeting our current agricultural demands.

Two major innovations we expect to see are improvement in yields from energy crops, and choosing energy crops that can provide multiple products. As we discuss further in the next chapter, switchgrass has the potential to more than double its per acre yield between now and 2050. It also contains more protein per ton than soybeans. This raises the exciting potential for soybean farmers to choose a new crop that can be sold for both its protein value and its energy value. We examine these two innovations in detail but believe that farmers will come up with others that we have not conceived of.

These innovations hold great promise for those regions of the country where switchgrass will be the most competitive and where soybeans are currently grown. Taken together, this includes most of the United States east of the Rockies. Switchgrass will be most competitive in the Southern Plains states and the Southeast, and soybeans are currently grown across the Corn Belt and up the East Coast.

While not central to our analysis, it is important to understand that the alternative to integrating cellulosic biomass demand with other current agricultural demands could also be good for farmers and taxpayers. If these demands are not integrated, then cellulosic biomass will have to prove more profitable based just on its energy value than other agricultural products. To the extent that such crop conversion does happen, it would actually be good for all farmers, not just the farmers who provide the material. As acres are converted from their current crops to energy crops, the value of the remaining traditional crops being produced will go up—less supply will lead to higher values. Higher values in turn mean the government will pay less in price support subsidies, meaning that taxpayers will benefit as well.

Modeling done by the University of Tennessee for this project gives an indication of how these dynamics could play out.[6] The model does not allow for innovative integration, so it can shed light only on the potential for crop conversion. In a hypothetical scenario where switchgrass had a value of $40 per dry ton (for comparison, current corn prices are about $67 per ton), the model predicts that by 2025 farmers would choose to plant 28 million acres and produce 200 million dry tons. These farmers would have net returns (as measured by the value of their products and government payments, less expenses) greater than $5.1 billion each year. However, total farmer net income would increase by about $12 billion, or 32 percent over a baseline based on prices forecast by the USDA. Furthermore, these benefits would be distributed across the country.

Figure 1 shows the geographic distribution of benefits that would result in 2025.[7] Farmer income goes up in just about every part of the country, with the largest increases occurring in the Plains states and the Corn Belt.

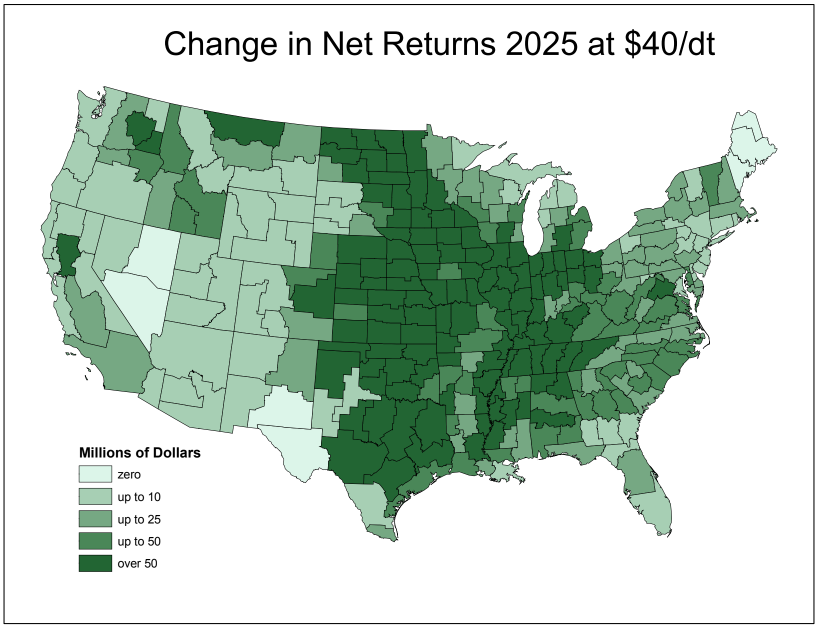


Figure 1. 2025 Change in Total Net Returns Relative to USDA Baseline Due to Switchgrass Market

These spillover benefits from cellulosic crops make biofuel policies that could encourage the development of a market for biomass important policies for the entire farm community. In the face of increasing uncertainty about what agricultural policies will look like after the 2007 Farm Bill, the World Trade Organization (WTO) agricultural subsidy rulings on U.S. cotton and European sugar, and the on-going WTO negotiations on agricultural subsidies, biofuels policies may offer a new tool for ensuring the viability of the U.S. agricultural sector.

Farmers will need to know a lot more about switchgrass or any other dedicated cellulosic biomass crop before they devote substantial acreage to it. Switchgrass is a perennial and while it can produce some commercial value even in the first year, it makes financial sense only when cultivated for six to ten years. Farmers will not lightly make such a commitment, and this is part of why further feedstock research, development, and demonstrations play such a central role in our recommendations.

BIOFUELS CAN OFFER A BOOST FOR THE ECONOMY

We believe that once established as a commercially mature industry, cellulosic biofuels can be cost-competitive with gasoline and diesel, and in the next chapter we do some detailed economic analysis to show how. Just as important, we believe that even if prices of gasoline and diesel compete with those of cellulosic biofuels, a major push to reduce our oil dependency will still be good for our economy. Our dependency on oil imposes a wide range of costs on us. There are the environmental costs of gasoline and diesel, including, lost productivity, premature death, and habitat destruction. There are the security costs of gasoline and diesel, including the cost of using our military to keep oil supply lines safe. And there are the indirect economic costs of oil including, the massive subsidies we give the oil industry, our balance of trade, and our vulnerability to oil price volatility.

If we accounted for all of these costs when we calculated the cost of a gallon of gasoline or diesel, it’s likely that we would find that biofuels are already cost effective. For now, though, our research focuses on the traditional costs of these petroleum fuels. There are essentially two scenarios to consider. First if biofuels and increased efficiency stalled the demand for oil, oil prices would decline—just like in a normal competitive market. Biofuels look less competitive, but the economic benefits are tremendous. If the price of every gallon of gasoline and diesel sold in the United States today were just one penny less, Americans would have $1.7 billion more in their pockets each year.[8]

ENERGY CROPS, AGRICULTURAL POLICY, AND THE WTO

Recent rulings by the World Trade Organization (WTO) give farmers another reason to look seriously at policies that support cellulosic biofuels. In the last year, the WTO has found U.S. price supports for cotton and European Union subsidies to sugar farmers to be illegal. Developing countries' successful challenge of these subsidies could create a precedent that jeopardizes price supports for other heavily subsidized crops in the United States, including corn, soybeans, and wheat. This potential seems to have been implicitly recognized by the United States in ongoing WTO negotiations over agricultural subsidies in which the U.S. negotiators have agreed to an initial 20 percent reduction in subsidies on certain key crops.

Policies to promote biofuels may offer an important new tool in maintaining the vitality of farmers in the United States in the face of these pressures. The conversion of even relatively small amounts of land to an energy crop such as switchgrass can increase the value of the remaining amount of traditional crops and thus reduce agricultural subsidies that are tied to crop prices.

Importantly, there is good reason to believe that policies to encourage energy crops are legal under the WTO. While the recent WTO rulings have found that federal crop price supports distort international trade and therefore must be reduced, measures to promote farm-based renewable energy and energy efficiency, including certain subsidies for dedicated energy crops like switchgrass, are likely to be exempt from WTO restrictions.

Alternatively, OPEC might reduce production and keep supply tight enough that prices would basically stay the same. This is OPEC's stated policy, but their ability to maintain prices over a long period of time is questionable. As biofuels start to compete, the price of gasoline and diesel stays the same. This makes biofuels look increasingly attractive. The benefits, however, are only as large as the market for biofuels. If biofuels are one penny less and we use only a billion gallons, then we will save only $10 million. If, however, we replace all of our gasoline and diesel with biofuels, the benefits would be the same $1.7 billion as in our first scenario.

In other words, the scenario in which biofuels are more expensive than petroleum fuels, but only because they drive the price of these fuels down through competition, produces larger economic benefits. Unfortunately, under this first scenario, policy makers are likely to have an increasingly difficult time justifying biofuels unless everyone understands that biofuels are driving down the price of gasoline and diesel.

Based on our detailed analysis of the potential for mature biofuels technologies, we believe that ethanol could be produced at prices as low as $0.39 per gallon. This is the equivalent of gasoline at $0.59 per gallon, which is well below both the average price for the last four years, which was $0.91 per gallon, and a forecast price for 2025 of $0.79 per gallon, based on DOE forecasts for the price of oil. At the end of this report, we lay out a plan to replace more than 100 billion gallons of gasoline with biofuels. If this was sold at $0.59 instead of $0.79 per gallon, that would generate a savings to our economy of $20 billion per year. Achieving the maximum oil displacement and greenhouse gas emissions reductions increases the price of biofuels, but there are combinations of technologies studied for this report that will bring tremendous benefits in every regard.

Of course, in the next 10 to 15 years—the time frame required to develop technologies that can produce biofuels cost-competitively—many things could dramatically change the price of oil, and almost all of them have nothing to do with biofuels. Wars, new oil discoveries, and technology breakthroughs for heavy oils could all lead to dramatic price changes.

A long-lasting, significant drop in oil prices could delay the date when biofuels become cost competitive. However the basic context is one of steadily increasing demand and steadily increasing price. Oil price increases such as we have seen over the past year, may make it easier for biofuels to compete. And it is worth noting that the best situation for biofuels is one in which high oil prices drive the rapid adoption of biofuels and, in turn, biofuels drive down the cost of oil but not to the point where gasoline and diesel are cheaper than biofuels. If international demand continues to grow while the rate of discovery of new oil reserve continues to decline, this best-case scenario may well turn out to be the most likely.

The bottom line is that if we move quickly to develop biofuels that can be produced at costs competitive with recent gasoline and diesel prices, the net effect on our economy will be positive no matter how the dynamics play out.

BIOFUELS CAN HELP CLEAN UP THE ENVIRONMENT

At every stage—from growing the crops through to burning biofuels—cellulosic biofuels can provide important environmental advantages if we reward environmental performance sufficiently. The bulk of these advantages would come from reducing our dependency on oil, but many also would come from growing a crop such as switchgrass that has a dramatically smaller environmental footprint than traditional row crops.

- The potential environmental benefits of greatly reducing our oil dependence through an aggressive package of fuel efficiency and biofuels are enormous.
- The transportation sector is responsible for approximately 42 percent of carbon dioxide emissions and 27 percent of overall global warming pollution in the United States.[9]
- The air pollution released by burning gasoline and diesel produces smog and soot that contribute to tens of thousands of premature deaths in the United States each year.[10]
- Sulfur and other pollutants released by burning gasoline and diesel produce acid rain. This is deposited in waterways, where it joins other toxic runoff from leaking vehicles, gas stations, and fuel storage tanks.
- Drilling for oil despoils wild places on land with roads through pristine wilderness and seismic testing in sensitive habitats.
- Oil spills from tankers and offshore platforms dirty our water, deposit in seafloor sediments, and poison marine life.

Vehicle efficiency and smart growth can reduce our dependency on oil by at least half over the coming decades, but to get beyond that we need an alternative to oil. The challenge is to avoid simply shifting environmental burdens from one part of the world and one part of the environment to another. Table 1 summarizes the environmental impacts that must be considered when evaluating biofuels.

In assessing these impacts, we have done an extensive literature review and new modeling of many of the impacts that can be readily quantified. A particular challenge in assessing biofuels comes in thinking them through at every stage of production and every stage of development—from crops through to using biofuels and from current technologies through to the most advanced configurations.

To do a full life cycle assessment of the environmental impacts of biofuels, the impacts should be compared to the alternatives. Fortunately, in terms of energy use and global warming pollution we have been able to draw on the GREET model from Argonne National Laboratory. This model is by far the most thorough look at energy use and air emissions for a wide variety of transportation fuels. Based on an updated version of this model that includes the innovations we are considering in this report, we can assess oil use and global warming pollution. And the results are extremely positive.

Advanced biofuels technologies coproducing biofuels and electricity should be able to displace more than 2 barrels of oil and 1.28 tons of greenhouse gases per dry ton of biomass used. This means that in the aggressive biofuels scenario we lay out in Chapter 7, by 2050 we could displace more than 7 million barrels of oil per day, the equivalent of nearly half of all the oil we currently use in the transportation sector. We would also be able to avoid nearly 1.7 billion tons of greenhouse gas emissions (measured in tons of CO_2 equivalents). This is equal to more than 22 percent of our total greenhouse gas emissions in 2002.[11]

In the areas of water, soil, habitat, and land use, we have no readily available inventory of environmental impacts from gasoline and diesel production. For impacts in these areas, we detail them as best we can but do not compare them to the status quo for petroleum fuels.

Nevertheless, these other benefits should be substantial. Switchgrass is a native perennial that should have significant environmental advantages in comparison to traditional row crops such as corn and soybeans: between one-half and one-eighth the nitrogen runoff, between 74 and 121 times less soil erosion, an increase in soil carbon levels rather than depletion, and providing habitat to at least twice as many and perhaps five times as many different species of birds.

The air quality benefits of using pure or high-percentage blends of biofuels are also impressive in the existing fleet. Biofuels have almost no sulfur, and they produce less carbon monoxide emissions, fewer particulate emissions, and few toxic air pollutants. Over time, with improvements in tailpipe controls and the cleaning up of gasoline and diesel, these air pollution benefits are likely to be reduced but not eliminated. Also the use of low-percentage blends of gasoline in the existing fleet is highly controversial because it can result in increased nitrogen oxide and volatile organic compound emissions, both of which contribute to urban smog. However, the newest vehicles can largely eliminate these impacts, meaning that this is a transitory problem. We are convinced that with appropriate regulatory safeguards and carefully crafted policies, these impacts can be kept to acceptable levels during an aggressive push toward a biofuels future.

Table 1. Summary of Environmental Impacts That Must Be Evaluated for Biofuels

Biofuel Stage	Air/climate	Water	Soil	Habitat	Land use
Growing switchgrass	Air pollution including GHGs from cultivating, harvesting and soil carbon sequestration; fertilizer/ pesticide/ herbicide production and application.	Water pollution from fertilizer/ pesticide/ herbicide runoff. Water use.	Soil fertility and quantity.	Wildlife use. Monoculturing. Use of genetically modified crops.	Resource sufficiency given competing demands for land for food and other higher-value uses.
Producing biofuels	Air pollution including GHGs from fuel production processes including the production of coproducts.	Water pollution including thermal pollution from production and waste disposal. Water use and loss to evaporation.	Contamination from waste disposal.		Footprint of plants.
Using biofuels	Air pollution including GHGs from combustion and evaporation.	Water pollution from spills during fueling and storage and from deposition of air pollution.	Contamination from spills during fueling and storage.		

NRDC and UCS base their support of cellulosic biofuels on the literature review and the analysis done for this report. While we can only summarize this here and in the next chapter, we hope it will start to address the concerns of the environmental community. Similarly, we hope it will help the agricultural community understand these concerns and recognize that only by addressing them head on and, where necessary by supporting appropriate regulations will biofuels be able to garner the broad support they will need to achieve the scale of development that we have forecast here.

SETTING PRIORITIES

If we want to produce an alternative to oil that is truly good for the whole country, we must make fair treatment of farmers and the environment as central to our policies as producing cost-effective biofuels. For both farmers and the environment, the greatest challenge lies in the transition from where we are today to a future where biofuels play major, sustainable roles in our transportation energy supply. Currently corn growers produce more than 3.1 billion gallon of corn ethanol per year. This requires more than 9 million acres of corn and is a very important source of income for many farmers. For farmers, biofuels policies must create continuously expanding opportunities and crop demand without stranding existing investments in current technology. Even a transitory dip in demand or a disruptive technology transition would be devastating to farmers.

What is bad for the existing biofuels industry would also be bad for the long-term success of biofuels in general. The existing industry provides the foundation from which a much larger biofuels industry can be launched. This is true both in terms of the experience and market building that is occurring through corn ethanol, and also literally in that corn fiber and corn stover are likely to be important sources of cellulosic biomass. Moreover, existing corn ethanol mills are likely to provide the testing ground for many next-generation biofuels technologies as they move from the lab to full-scale commercialization. While there may be a revolution in biofuels technology, the change from the biofuels industry of today to that of the future is much more likely to be a process of evolution, and environmentalists should work just as hard as farmers to make sure there are policies in place that make the transition smooth.

On the environmental side, we have already alluded to the air quality impacts associated with the way we currently use blends of small amounts of ethanol with gasoline in the existing vehicle fleet. On a pathway to using pure biofuels in vehicles optimized for these fuels, these impacts are transitory, but they must be taken seriously and minimized or they will act as barriers to broad support of biofuels. The environmental benefits of growing a cellulosic biomass crop are also not guaranteed. All crops, even switchgrass, can be grown without regard for water pollution and wildlife habitat. Furthermore, the restriction that we put on our analysis to look only at land currently under cultivation is not inherent in the market for biomass. Other sources of biomass will no doubt be drawn into the market; their impacts must be evaluated and in some cases their use will need to be regulated.

The interests of farmers and environmentalists can best be assured through a concerted and cooperative effort of the agricultural and environmental communities. While there are specific policies that we will address in Chapter 2, a collaborative effort between these two communities is crucial not only to enacting these policies but to capturing their full benefits. And the first steps in establishing such a collaborative must be for each community to recognize the central issues and concerns of the other and for each community to commit to addressing these concerns. We hope that this report, in addition to providing a vision of a biofuels future, will help in the formation of such an agricultural-environmental collaborative.

CHAPTER 2

THREE STEPS TO MAKE BIOFUELS AFFORDABLE AND SUSTAINABLE

Breaking our addiction to oil is going to require a long-term commitment to increasing efficiency, creating more livable communities that do not require as much driving, and making biofuel affordable and sustainable. Focusing now on achieving the aggressive vision for biofuels that we have started to lay out, three key steps are essential:

- Investing in a package of research, development, and demonstration policies that create the innovations and advances needed for a large-scale, competitive biofuels industry.
- Funding deployment policies that drive the development of the first billion gallons of cellulosic biofuels capacity at a price approaching that of gasoline and diesel;
- Adopting a renewable fuels standard and flex-fuel vehicle requirement.

STEP 1: INVEST IN RESEARCH, DEVELOPMENT, AND DEMONSTRATION

We recommend a package of policies with the broad goal of developing a cellulosic biofuel industry by 2015 that is cost-competitive with corn ethanol and moving rapidly toward cost-competitiveness with petroleum fuels. To achieve such an aggressive commercialization schedule, research, development, demonstration, and deployment (RDD&D) will need to be pursued on nearly parallel tracks. We recommend two basic policies: 1) a research, development, and demonstration (RD&D) policy from 2006 to 2012 costing a total of $1.1 billion, and 2) a deployment policy from 2006 to 2015 costing a total of $800 million. Taken together, these policies would create about 1 billion gallons of biofuels capacity and advance the technology to a state where it is capable of producing biofuels at costs competitive with those of gasoline and diesel.

The goal of federal programs addressing RD&D relevant to biomass conversion should be to establish the scientific and technological foundation necessary to rapidly deploy industrial processes producing biofuels from biomass. Although direct support for commercialization has many benefits, the rate, extent, and probability of realizing these benefits for biofuels will be greatly increased by an aggressive, targeted effort directed toward precommercial RD&D. Of course, with a range of state and federal subsidies generally available to energy projects, the line between commercial and precommercial can be blurred. We draw the line based on both scale—precommercial RD&D produces relatively little, if any, finished product—and economics—any finished product produced cannot generate enough revenue to make a plant profitable even with any other subsidies available.

As commercialization starts (with larger plants that can produce a profit), the investment community will look to RD&D to determine the viability of technology and the likelihood of a project's success. Precommercial RD&D not only advances the technology but greatly reduces the perceived risk associated with the technology. While precommercial RD&D is clearly an investment in commercialization, the private sector is unlikely to invest on the scale or at the speed that we need if we are to start to wean ourselves from oil. The private sector cannot make biofuels happen without government support; the potential rewards are too long-term and too many of the benefits are societal and hard for a single company to capture.

RD&D activities can be categorized with respect to three key areas of technological focus: 1) overcoming the recalcitrance of cellulosic biomass, 2) enabling product diversification including different fuels, animal feed protein, and chemicals, and 3) making advances in feedstock production. Of the technological challenges discussed earlier, overcoming the recalcitrance of the cellulosic biomass is the greatest impediment to realizing the potential for biofuels production. Whether through pretreatment, biological processing, gasification-based thermochemical processing, if biofuels are to meet a large portion of our transportation fuel needs, then we must be able to use more than just starch from biomass.

RD&D activities can also be classified by the way in which they add value. There are primarily three levels: 1) innovative technological advances, 2) better understanding of applied fundamentals, and 3) process integration, scale-up, and demonstration. Innovations to improve biomass processes are required in order to develop processes that are sufficiently low in cost, high in efficiency, and environmentally benign to compete with conventional energy sources on a large scale. As discussed in greater detail later, the types of innovations needed include developing superior microorganisms, pretreatment processes, syngas cleanup systems, pressurized feeding to gasifiers, protein separation processes, crop yield improvements, coproduction of biofuels, power, and other value-added products, and crop harvesting and handling systems. Fortunately, innovations in all of these areas are readily foreseeable.

To estimate the cost of the RD&D efforts needed to ready biofuels technology for deployment, we made a general assessment of how much each category of technology would need and then built up an estimate from detailed considerations of the different levels of RD&D work each category needed. A total investment of about $1.1 billion from 2006 through 2012 should produce a regular flow of advances that can be used in deployment and move the technology to a point where most of the remaining development can be done through learning by doing at commercial competitive facilities.[12]

Table 2. Breakdown of RD&D Support

Necessary ratio and level of support ($ million)	Recalcitrance of biomass	Coproducts	Feedstock
	45%	30%	25%

Applied fundamentals	15%	$74	$50	$41
Innovation	35%	$173	$116	$96
Demonstration	50%	$248	$165	$138

The RD&D programs can be implemented through the Biomass R&D Development Act of 2000, which was first funded in the Farm Bill of 2002. The basic approach established through this act involves open and competitive solicitations with awards made regularly based on expert peer review of proposals. Currently biofuels RD&D grants are funded at $75 million total over six years, but this is up for reauthorization in the 2007 Farm Bill. In addition to dramatically increasing the funding, we propose adding the funding targets for different levels of RD&D and different technical focus areas.

We recommend that innovation receive 35 percent of the funding and applied fundamentals receive 15 percent. A combination of those funding amounts—50 percent—should be targeted at demonstration. Within the areas of focus, enabling conversion of the cellulose portion of biomass should receive 45 percent of overall funding, developing coproducts such as power, protein, fuels and chemicals should receive 30 percent, and feedstocks should receive the remaining 25 percent. Table 2 provides a breakdown of how these funds would need to be spent.

In many ways the ratio of support between categories of RD&D and levels of RD&D are as important as the amounts of funding. Under the Biomass R&D Act, the Department of Energy and the USDA share equally the responsibility of making funding decisions. Going forward, it may make more sense to divide administration of the RD&D budget among the categories rather than simply splitting it down the middle. Either way, the agencies should be required to meet these funding targets overall and should strive to meet them on an annual basis, the quality of the proposals permitting. Adjustments to the overall targets maybe necessary, but they should be undertaken only after careful analysis and public input.

Other key RD&D recommendations that should be incorporated into a reauthorized Biomass R&D Development Act include:

- Open solicitations should use a consistent approach year to year.
- Objectives for the solicitations should be clearly stated, with no areas of special interest.
- Results of R&D projects supported by these funds should be made public to enable a competitive industry to develop.
- Demonstration should require a 20 percent spending match.
- Innovation and applied fundamental R&D should not require a spending match.
- A range of lead institutions should be acceptable.
- At least half of the reviewers for each area and type of R&D should be external experts drawn from outside of the USDA and the Department of Energy.

WHY RESEARCH AND DEVELOPMENT SHOULD HAPPEN AT THE SAME TIME

We recommend starting deployment incentives at the same time as RD&D policies. The deployment policy needs to be pursued in parallel with the RD&D policy to ensure rapid evolution of the technology. While innovations are needed to bring about cost-effective and sustainable cellulosic biofuels, technologies exist today that can function on a commercial scale and that will provide a wealth of information about the integrated operations of technologies. For example, the development of biomass Fischer Tropsch production might benefit from piggybacking a biomass gasification system onto a coal-to-Fischer Tropsch facility, such as the pilot-scale project (5,000 barrels per day capacity) proposed and supported with DOE cofunding for Gilberton, Pennsylvania. Such facilities can serve as the launch pads for the technologies developed by the RD&D policy both in a literal sense—in that these facilities can be expanded, allowing for the rapid adoption of innovations—and through the learning-by-doing that these facilities will allow.

STEP 2: FUND DEPLOYMENT STRATEGIES FOR THE FIRST BILLION GALLONS

There should be three primary goals for deployment policies. First, they should encourage construction and operation of enough capacity so that, in combination with aggressive RD&D, plants built after 2015 are technically capable of producing biofuels at costs competitive with corn ethanol and ideally with gasoline and diesel. In other words, that the policies need to actually get projects built, successfully operating, and using innovative technology. At the same time they need to minimize the risk of wasting public dollars. To do this, they should interfere as little as possible with private sector due diligence. Finally, it is crucial that the policies ensure the industry is self-sufficient when the policies expire.

Achieving these goals requires overcoming a host of challenges. With developed technologies, performance-based incentives have proven very effective as deployment policies. The production tax credit for wind is a prime example. However, for plants relying largely on technologies never used before on a commercial scale, there is a significant barrier in arranging financing because of the risk of failure or poor performance. Because performance-based incentives pay only for successful operation, they can reduce but not eliminate the finance barrier.

When funds are available, the terms imposed by debt lenders regarding performance guarantees, equipment redundancy, feedstock price and supply guarantees, and credit worthy off-take agreements make projects much more expensive and greatly reduce the profits available to the developer and equity investors. For their part, equity investors want to see very high potential returns, which are hard to show while meeting lenders' requirements; the alternative is to use very high equity levels, which greatly reduces the profits to the developer.

Each project will face financing challenges to a different degree making it hard to design a one-size-fits-all incentive mechanism. Furthermore, as the technology develops, the challenges will shift, allowing production incentives to play an increasingly important role. Unfortunately, subsidies tend to lead to addiction on the part of industry; thus subsidies are hard to eliminate and the industry cannot stand on its own. The industry will plan for independency and public dollars will be better spent if a phase-out of support is clearly built into policies from the beginning.

Generally speaking, the government is poorly equipped to determine the most promising projects and to determine how the needs of the industry change over time. Furthermore, government incentives that are subject to annual appropriations are high risk and greatly discounted by financiers. There is a lot of history of using loan guarantees, which can effectively make financing available, but as traditionally applied, these also reduce the incentive to the financial community to perform a rigorous due diligence review on projects. Furthermore, loan guarantees are often viewed as a sign of a technology that does not work rather than a badge of approval. The result: failed projects that have cost taxpayers millions.

To achieve our goals in the face of these challenges, we recommend a deployment policy that offers a variety of incentives, including incentives targeted at the major barriers to financing and production. Such a policy should also let the developer mix and match incentives under an overall cap on the value of the incentives chosen. In addition to choosing the incentives, developers would also get to choose one of three pools from which to draw their support. Each pool would have a different cap on the value of incentives. Table 3 summarizes the incentives and pools; we will discuss them each in more detail below.

Table 3. Summary of Deployment Policy

<table>
<tr><td colspan="5">Menu of Incentives Available to Developers</td></tr>
<tr><td>Item</td><td colspan="4">Description</td></tr>
<tr><td>A</td><td colspan="4">Bond insurance, for feedstock supplier, valued at cost of policy</td></tr>
<tr><td>B</td><td colspan="4">Bond insurance, for product purchaser, valued at cost of policy</td></tr>
<tr><td>C</td><td colspan="4">Efficacy insurance, for technology nonperformance, valued at cost of policy or total liquidated damages covered</td></tr>
<tr><td>D</td><td colspan="4">Production incentive, fixed $ per gallon paid over first five years of operation</td></tr>
<tr><td colspan="5">Guidelines for the Value of Incentives Available to Developers</td></tr>
<tr><td rowspan="2">Pool</td><td colspan="2">Maximum available to a single project the lesser of:</td><td rowspan="2">Total available in pool</td><td rowspan="2">Total capacity limit in pool (Billion Btu per year)</td></tr>
<tr><td>% of overnight cost</td><td>Total value</td></tr>
<tr><td>I</td><td>50%</td><td>$20,000,000</td><td>$200,000,000</td><td>3,785</td></tr>
<tr><td>II</td><td>25%</td><td>$40,000,000</td><td>$300,000,000</td><td>26,495</td></tr>
<tr><td>III</td><td>10%</td><td>$50,000,000</td><td>$400,000,000</td><td>75,700</td></tr>
</table>

We recommend that the menu of incentives available to a developer consist of bond insurance for feedstock suppliers, bond insurance for biofuel purchasers, efficacy insurance for the fuel production technology, and a production incentive that pays a fixed amount per gallon for the first five years of operation. The bond insurance is important because debt financiers generally require feedstock and off-take guarantees, which can be provided only by credit worthy companies. This greatly limits the number of suppliers and purchasers that a project can contract with, driving up the cost of supply and driving down the value of the product. Bond insurance is readily available and, for a price, can effectively transform any supplier or purchaser into a credit worthy partner. The government incentive would cover the cost of this insurance, subtracting the cost from the overall cap on incentives available to a project.

Efficacy insurance (also known as system performance insurance or nondamage insurance) covers failures in performance not caused by equipment breakdown or mistakes in design. In other words, efficacy insurance pays when the technology simply does not work as well as the developer had predicted. The policy either pays to bring the performance up to specification or provides liquidated damages up to the value covered by the policy.[13] Hartford Steam Boiler offered system performance insurance to the Masada concentrated acid hydrolysis ethanol project in 2000, but Hartford Steam Boiler was bought by AIG, which canceled the policy before the Masada plant was built. At this point no insurance companies are offering this type of insurance, so the challenge would be finding a way for the government to induce insurance companies to offer it again for new biofuels plants.[14] It is likely that the cost would be very high, at least initially. If a private insurance policy cannot be developed, then the government could offer the policy, subtracting from the project's overall incentive cap the full cost of the liquidated damages covered.

The developer could also take any amount of its total available incentive as a production incentive which would be paid out over the first five years of operations on a fixed dollar per gallon basis. To encourage maximum performance, the performance incentive would be calculated by dividing the amount of incentive that the developer chose to collect as a production incentive by expected capacity during the first five years. This value would then be fixed and the developer could collect the total only if it met or exceeded the expected production levels.

In addition to choosing a mix of incentives, developers would have to choose one of three pools from which to draw their support. As summarized in Table 3 above, the first pool limits support to the lesser of 50 percent of the overnight costs of a project and $20 million, the second pool limits support to 25 percent and $40 million, and the third to 10 percent and $50 million. The total funds and total amount of fuel production capacity in each pool would be limited and would be subscribed on a first-come-first-served basis. For instance, the first pool has a total limit of $200 million and a capacity limit of 3,785 billion Btu per year (the equivalent of 50 million gallons of ethanol), half of which must be in the form of biofuels. Because the maximum value per project is capped at $20 million, this pool could support up to 10 projects. However, if four projects each produced 946 million Btu, then the pool would be closed. If a project fails or does not use all of its incentives, then these funds go back into their respective pools and are made available to other projects, assuming the pool is not closed.

No doubt, this is a complicated way to offer support for deployment, but if we look back at our goals and challenges, there are good reasons for each of the features offered by this approach. For instance, production incentives minimize risk of wasting public funds because these policies pay only for performance. In the menu of incentives, the production incentive would have the highest value to the developer and equity investors because it increases revenues, whereas the insurance-based incentives primarily cover the risk of lenders. Thus we expect developers to shift to production incentives as quickly as the market will allow, minimizing the risk of wasted public funds.

By limiting the total value of incentives, we force developers to allocate the available incentives in the way that makes the most sense for their project. By using both a percent of overnight costs and a dollar cap, we ensure that the smaller pilot projects (on the scale of Iogen's Ottawa enzymatic based plant) that we expect to be developed first get a relatively rich level of support while the larger projects that come later can receive more per project but a much smaller proportional level of support. The reduction in support for larger plants also helps to prepare the industry to be self-sufficient.

The limits on total funding and total capacity for each pool establish a clear set of limits on the deployment policy, also forcing the industry to prepare for independence. Furthermore, since our interest is driving the development of biofuel capacity, not simply spending money, the capacity caps on each pool ensure that if the industry develops larger and more productive plants faster, then the public does not have to keep paying. Finally, by measuring capacity in terms of the energy value of the products produced but requiring at least 50 percent of each pool to be in the form of biofuels, we allow different configurations of bioenergy production to compete while ensuring overall that biofuels are advanced.[15]

STEP 3: ADOPT A RENEWABLE FUELS STANDARD AND FLEX-FUEL VEHICLE REQUIREMENT

While we develop a competitive cellulosic biofuel industry and after it is developed, we will need to continue to support the use of biofuels and to keep our broader objectives in mind. Existing biofuels, including corn ethanol, provide important security, environmental, and economic benefits. Furthermore, given the tremendous amount of investment in everything from oil refining to gas stations to our cars and trucks, our economy is so deeply locked into using petroleum fuels that simply because a biofuel becomes cost competitive with these fuels does not mean that it will easily be adopted. There is a lot of asset inertia that must be overcome.

We recommend the adoption of a renewable fuels standard that includes environmental performance standards and a requirement that all new light-duty vehicles be required to be flex-fuel vehicles. These measures can provide the steady pressure needed to start breaking our oil addiction and reducing the greenhouse gas emissions from the transportation sector while also ensuring a steadily increasing market for biofuels.

The 2004 Energy Bill (S.2095) is as a whole unacceptable to the environmental community, but it does contain a renewable fuels provision that is a start. This provision should be improved, adopted, and expanded over time to ensure that biofuels develop along a sustainable path. The renewable fuels standard as currently proposed would require that gasoline refiners, blenders, and importers sell or hold credits worth 4.1 billion gallons of ethanol by 2009 and 5 billion gallons by 2012. Gallons of ethanol produced from agricultural residues are credited as 2.5 gallons, and gallons produced from dedicated energy crops are credited as 1.5 gallons. A requirement that a small but growing percentage of the renewable fuels standard be met through cellulosic biofuels would be more powerful than this credit system and should be considered.

The renewable fuels standard is also linked to a waiver of liability for refiners that use methyl tertiary butyl ether (MTBE) as an oxygenate. In the near term, it is essential that the MTBE liability waiver be dropped because liability is crucial to ensuring that companies act responsibly, and to avoiding forcing taxpayers in the polluted regions to pay the multi-billion-dollar cleanup costs. The renewable fuels standard should also include provisions to safeguard air and water quality as the use of ethanol increases. Specifically, the oxygenate requirement that until recently drove the use of MTBE should be dropped, and non-attainment zones should be allowed to use whatever gasoline they want, provided it meets a new, rigorous environmental standard. Finally, the EPA should be required to develop regulations to minimize the risk of water pollution from fuel additives so that the damage caused by MTBE is not repeated.

In the long term as a viable cellulosic biofuels industry develops, the renewable fuels standard should be shifted from simply requiring ethanol to allowing all forms of biofuels to compete on a performance basis. There should be three performance criteria used: 1) reduced oil consumption, 2) reduced greenhouse gas emissions, and 3) maintenance of, or improvements in, air and water quality, soil fertility and stability, and wildlife habitat. Performance of different fuels should be measured on a life cycle basis, and a method of assigning each fuel-technology combination would need to be developed.[16]

Simply requiring renewable fuel production is likely to be insufficient for moving the transportation market forward in adopting these new fuels. With nearly all new vehicles designed for exclusive use of gasoline (to which limited amounts of ethanol can be added), passenger vehicles capable of operating solely on ethanol will also need to see a larger market share. Unfortunately, current vehicle policy to encourage FFV production actually increases oil consumption. Under Corporate Average Fuel Economy (CAFE) standards, automakers garner added credits for building ethanol-capable vehicles even if those vehicles never see a drop of ethanol. This has proven a lucrative loophole for automakers, who can use the credits to boost their fleet fuel economy without actually delivering more efficient cars. The result has been lower real-world fuel economy than required by law. The short-term policy priority is to close the FFV loophole, replacing it with a system in which CAFE credits go to vehicles based on the amount of ethanol they consume. The end result will be a system that rewards oil savings from new cars and encourages the use of ethanol fuel. The long-term solution to solving the traditional chicken-and-egg challenge of alternative fuel introduction may be to require ethanol capability for all new vehicles. There are no significant technical or cost challenges to such an approach, and we have assumed such a policy is in place by 2015.

WHERE THE FIRST PLANTS MIGHT BE BUILT

While large-scale penetration of cellulosic biofuels will require growing millions of acres of dedicated energy crops, the first cellulosic biofuel production plants will almost certainly use agricultural or forest residues. The environmental impact of using these resources needs to be better understood, and to ensure the sustainability of the pathways we have studied, we have not relied on these residues. However, these residues are cheap and plentiful and will allow the first plants, which will be more expensive themselves, to avoid also having to pay the high cost of the first energy crops. Evidence of this can be seen in the feedstock used in the proposed cellulosic ethanol plants and the one existing demonstration-scale facility. The feedstocks used by these plants include rice straw (a residue from rice cultivation), sugarcane bagasse (a residue from sugarcane cultivation), wheat, oat, and barley straw (a residue from cultivation of these grains), other agricultural residues, and municipal solid waste cellulosic residue. These plants were proposed for California, Louisiana, and New York, and the demonstration plant was actually built in Ottawa. These are all places with ample supplies of these residues.

A 1999 study by Oak Ridge National Lab estimated that at $30 per dry ton, there would be more than 68 million tons of mill waste, forest residues, and agricultural residues—enough to produce more than 7 billion gallons of cellulosic biofuel. The states listed in Table 4 below accounted for nearly 70 percent of these residue sources of cellulose.[17]

In addition to the low cost, some of the first plants are likely to take advantage of existing infrastructure. For instance, corn ethanol facilities already have all the equipment needed to handle ethanol and wastes. Such a facility could start by adding a test bed to prove the potential for any of the key technology advances we discussed earlier and then eventually expand, adding a complete cellulosic biofuels production line. The same evolution could happen on the thermochemical side, with a biopower facility adding a gasification and biofuels synthesis production line.

While state policies or special case resources may attract the first cellulosic fuel plants anywhere, all else being equal, the RBAEF team expects the first plants to be located at sites with low-cost feedstock and existing bioenergy infrastructure.

Table 4. States with Low-Cost Cellulosic Residues.

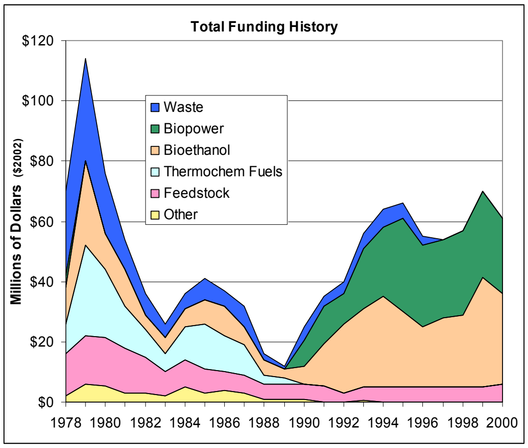
Top 10 Sources of Residues at $30/Dry Ton
Tennessee
Pennsylvania
Missouri
West Virginia
Mississippi
Kentucky
Colorado
Virginia
Georgia

WHY EXISTING BIOFUELS POLICIES ARE NOT ENOUGH

A lot of money and effort has been spent building a market for ethanol made from the starch in corn kernels. There have been large improvements in technology since these efforts started in earnest in the late 1970s, and large improvements in the productivity of corn. This has made biofuels a small but important part of our transportation energy mix. Ethanol currently provides about 2 percent of our transportation energy needs, mostly as a fuel additive for gasoline, where it increases the fuel octane rating and oxygen content.[18]

There is room for improving corn growing and corn kernel fermentation into ethanol, but these improvements are expected to be incremental, not revolutionary. As a result, while the price of corn ethanol (currently at least twice that of gasoline on a Btu basis) will continue to come down, few expect corn ethanol to become commercially competitive with gasoline or to be able to replace gasoline at a large scale in the foreseeable future.

While there have been significant technological developments in the conversion of cellulosic biomass to fuels, none of these technologies have resulted in commercially viable facilities. Why then should policy makers believe that technology will become available now in response to any new policies? The simple answer is that we have never mounted an effort remotely commensurate with the challenges and potential benefits involved. The relatively small amount of funds devoted to this has resulted in an inadequate level of commitment and the absence of a disciplined, long-term R&D effort directed toward making biofuels a large-scale alternative to gasoline and diesel. The Department of Energy spends about two-thirds of the total federal funding in bioenergy, with most of the remaining one-third overseen by the Department of Agriculture (USDA). Figure 2 illustrates how the Department of Energy budget and focus have fluctuated over time as administrators have faced the daunting task of trying to deliver on the promise of bioenergy with an inadequate and constantly changing budget.[19] Discontinuity in research does much more than delay ultimate success in proportion to the period of reduced activity. It devastates progress due to a loss of knowledge that occurs in these periods of hiatus.[20]



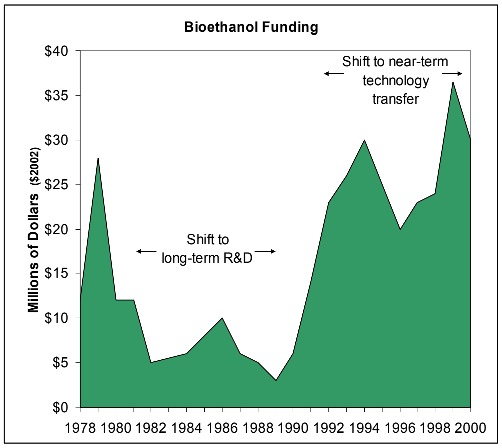


Figure 2. Department of Energy Biomass R&D Funding (1978–2000)

BUILDING A NEW AGRICULTURAL AND ENVIRONMENTAL COALITION

There are many opportunities coming in the next few years to implement biofuels policies. The renewable fuels standard is likely to come up for a vote next year. The McCain-Lieberman Climate Stewardship Act will be voted on. And debate on the 2007 Farm Bill will start in 2006 if not sooner. The Farm Bill will be important to biofuels both because of the energy title in the bill and because it will be the most likely vehicle for addressing any changes in agricultural policy required in response to World Trade Organization rulings and agreements. Plus, it is entirely possible that bills solely aimed at developing biofuels will be introduced both at the federal level and in individual states.

All of these opportunities to advance biofuels will also be opportunities for the agricultural and environmental communities to work together and start to rebuild mutual trust. If these communities can find common ground, they have the potential to be extremely powerful.

As discussed in the first chapter, a crucial first step is for both sides to start to understand the concerns of the other and commit to trying to address these concerns in policies they advance. For farmers, these concerns no doubt include the need to ensure that the evolution to cellulosic biofuels is a process of steadily expanding opportunities. For the environmental community, these concerns focus on ensuring that biofuels develop along a truly sustainable path. Biofuels can be a forum for developing an understanding of these concerns and a commitment to address them. Without a coordinated effort, biofuels may never happen on a large scale or may simply replace one set of challenges caused by oil with another caused by poorly developed biofuels. Done right, though, biofuels can improve the economics of all crop farming in the United States while offering essential environmental improvements to air, water, soil, and habitat across the country.

There are many next steps to follow this report. We have examined cellulosic biofuels produced from switchgrass to assess the sustainable potential of biofuels. First among next steps should be an analysis of adding corn stover processing to existing corn ethanol plants. Corn stover processing is a logical starting place for an evolution in the corn ethanol industry. It could potentially add more than 20 billion gallons of ethanol production, new income to corn farmers, and a clear place for the existing industry in the transition to cellulosic biofuels.

The authors of this report including NRDC and UCS believe that biofuels offer one of the most promising long-term options for addressing our country's dependence on oil and the impact of transportation on our global climate. We are committed to developing the agricultural-environmental alliances that will be needed to develop biofuels as an alternative to oil and to reduce the economic and environmental impacts of vehicle use. And this coalition should be only the beginning. The energy security, economic prosperity, and environmental protection benefits of biofuels should bring together many interests, and together we can turn this promising technology into a reality.

In this report, we argue that cellulosic biofuels can play a central role in greatly reducing our dependency on oil. We have laid out the technological advances needed. In this chapter we have proposed a package of policies that, if implemented carefully and consistently, could pave the way to a revolution in biofuels. The sooner we start, the sooner we will be able to reap the rewards.

CHAPTER 3

WHAT GROWING BIOMASS FOR BIOFUELS LOOKS LIKE

The first step in both the process of making biofuels and the process of developing a biofuels future is the raw plant material—the biomass from which biofuels are made. We must be able to grow enough biomass, grow it sustainably, and grow it profitably. Switchgrass, while just one of a number of potential cellulosic biomass crops, offers exciting potential on all fronts. It is a native prairie grass with great potential to increase its annual yield. As we'll see when we look at switchgrass more closely, these features are key to making a large biofuels industry possible on the land we currently have for crops, and sustainable.

In estimating the sustainable long-term potential for biofuels, growing biomass is the first step, followed by processing it into biofuels, followed by using it. At each stage, we have focused not on the performance of technologies as they are today, but rather on how we expect them to be once they have reached commercial maturity. How long it takes for these technologies to reach commercial maturity depends on their current state of development and, importantly, on the level of effort we put into developing and deploying them. If our recommendations in Chapter 2 are implemented, we expect biofuels could reach commercial maturity around 2015.

We have chosen a model feedstock—switchgrass—that has many attractive environmental features and the potential for significantly improved yields. We have also chosen promising approaches for converting cellulosic biomass into biofuels—biological and thermochemical processes—and have estimated how well these technologies will perform once they reach maturity. This allows us to estimate the sustainable production of biofuels. Finally, we have asked, if we start now to reduce our oil dependency, how efficient will our vehicles be in the future? Combining the resulting energy demand with our production estimates, we are able assess how important a role biofuels could play in meeting our long-term transportation energy needs.

In the next three chapters we look in detail at the environmental impacts of each stage of biofuels production and use so that communities that will be impacted by these stages will understand the pros and cons of biofuels. We also hope that this will help proponents of biofuels understand the range of concerns that must be addressed through careful research, clear communication, and, as necessary, appropriate regulations.

Bringing together all of the stages in Chapter 6, we assess a number of ways to use advanced technologies to produce different biofuels, biopower, and in some cases animal feed protein. We assess the ability of these different approaches to displace oil, reduce greenhouse gases, reduce other major air pollutants, and compete economically with gasoline and diesel.

CELLULOSIC BIOMASS AND WHAT YOU CAN MAKE FROM IT

To understand the importance of cellulosic biomass, including switchgrass, it is helpful to have a basic understanding of what's in cellulosic biomass and how we can turn it into valuable products. Cellulosic biomass is basically all the parts of a plant that are above ground except for the fruit and seeds such as corn, wheat, soybeans, and rapeseed. Technically, cellulosic biomass is the photosynthetic and structural parts of plant matter. Other examples of cellulosic biomass include grass, wood, and residues from agriculture or the forest products industry. Most forms of cellulosic biomass are composed of carbohydrates, or sugars, and lignin, with lesser amounts of protein, ash, and minor organic components. The carbohydrates, usually about two-thirds of the mass of the plant, are present as cellulose and hemicellulose—thus the term cellulosic biomass.

There are a number of ways to convert plant matter into fuels. The most common is the fermentation of corn kernels into ethanol. This process is essentially the same one used to make the various types of alcohol that people drink. This process is relatively simple because the sugars in corn kernels dissolve easily in water and thus are readily accessible to the microorganisms that do the fermentation. Importantly, the carbohydrates in cellulosic biomass will not dissolve in water. This makes them harder to ferment. However, when these carbohydrates are converted to soluble sugars, they too can be fermented by microorganisms (yeasts or bacteria) to ethanol. While this fuel is identical to that made from corn, we refer to it as cellulosic ethanol to be clear that it comes from a different source. Because the processes used to make cellulosic ethanol rely on microorganisms, we refer to them as biological processes.

Lignin, often 15 to 25 percent of the mass of the plant, is essentially not fermentable. It is, however, energy rich, and in fact chemically resembles soft coal. Lignin, alone or together with the carbohydrate portions of biomass, can be converted to fuel by thermochemical gasification—a relatively high-temperature process that produces a gas called synthesis gas, or syngas. This gas can be converted by catalysts into fuels or burned to make power. The thermochemical fuels that we are focusing on are Fischer Tropsch fuels and dimethyl ether.

Biological and thermochemical processing can be applied together—using the carbohydrates for biological processing and just the lignin for thermochemical processing. In fact, there is enough energy in lignin to power the biological process and produce fuel or power for sale. These types of coproduction opportunities play a central role in our analysis.

Specifically, the products we consider are ethanol, Fischer Tropsch fuels, dimethyl ether, power, and animal feed protein. The mature processing technology configurations we consider are biological processing using what is known as consolidated bioprocessing (CBP) and three forms of thermochemical processing—direct combustion with steam power generation, known as Rankine cycle power production, gasification-based power with gas turbine/steam turbine combined cycle, and gasification-based fuel production. Specifically, we have modeled the following combinations:

1. Ethanol from CBP and power coproduction from CBP residues via Rankine cycle
2. Ethanol from CBP and power coproduction from CBP residues via gasification
3. Ethanol from CBP and Fischer Tropsch fuels coproduction from CBP residues via gasification
4. Ethanol from CBP and power coproduction via Rankine cycle and animal protein coproduction
5. Fischer Tropsch fuels and power coproduction via gasification
6. Dimethyl ether and power coproduction via gasification
7. Power from Rankine cycle
8. Power from gasification

We have analyzed producing fuels and power from cellulosic biomass. Our analysis shows that both options have the potential to reduce similar amounts of greenhouse gases and that biofuels have the potential to be slightly more cost competitive with the traditional alternatives. In the end, we have chosen to focus on producing biofuels for two reasons. First and foremost, only by producing biofuels can biomass help displace a significant amount of our oil demand and thereby contribute to our energy security. Second is the related fact that biofuels are the only renewable source of liquid motor vehicle fuels. All other renewable energy options would require converting our transportation system to using gaseous fuels—doable but considerably more challenging. However, we recognize that biomass is an important source of renewable electricity in that it is the only renewable other than hydropower and geothermal power that can be turned on and off as needed. While power storage technologies may develop allowing us more options, currently other renewables are available only intermittently, such as when the wind blows and the sun shines.

Both thermochemical and biological processes can also be tuned to produce a range of industrial chemicals. Some of these may have very high value, but in comparison to transportation fuels would reduce only a small percentage of our oil use. For this reason, we have not focused on them. We recognize, though, that the coproduction of industrial chemicals can provide substantial additional revenue and allow the sale of fuels at much lower prices, and that this represents important opportunities for the chemical industry.

Note that we have not included hydrogen as a potential thermochemical fuel simply for lack of time. Hydrogen can easily be produced by further refining the syngas from thermochemical gasification. We expect to include both dedicated and coproduced hydrogen in future reports on our analysis. Given our findings that biofuels have the potential to displace nearly 8 million barrels of oil per day cost-competitively with gasoline and diesel, all of these alternative fuels deserve much larger and more concerted public support then they are receiving now.

GROWING BETTER FEEDSTOCKS

There are many potential sources of cellulosic biomass, including agricultural and forest residues and dedicated cellulosic crops. Each has it pros and cons. Farmers, food processors, paper mills, furniture manufacturers and others currently pay to dispose of some of these residues, and some others could be collected relatively inexpensively. However, as the demand for quantity and consistent quality and price of feedstocks increases, cellulosic crops are going to play an increasingly important role and most likely provide most of the feedstock for a biofuels industry on the scale discussed in this report. Two classes of energy crops have received the most attention in R&D efforts to date: woody crops such as hybrid poplars and hybrid willows, and herbaceous crops such as switchgrass. In this analysis we have focused on switchgrass.

Switchgrass is a prairie grass. There are two types of switchgrass—an upland variety, which thrives in well-drained soils, and a lowland counterpart found in heavier soils. Both are endemic to North America and have developed a natural resistance to pest infestation and disease, which helps make their yields both high and dependable.[21] Yields are crucial because they determine the total amount of land that would be needed to produce a given amount of biomass as well as the potential profitability of a farmer's land. Obviously, yield varies based on the local soil quality and climate. Thus, in field trials in the Southern Plains region, switchgrass averages about 4.3 dry tons per acre per year and in the Corn Belt region, yields average 6.0 dry tons per acre per year. Table 5 shows the spread of current yields across different regions of the country. On average, with today's varieties and agronomic practices, a yield of about 5 dry tons per acre per year is a reasonable expectation.

Table 5. Switchgrass Yields

Region	2004 Yield (dt/ac/yr)	Breeding Gains per Year (dt/ac/yr)	Projected Future Yields (dt/ac/yr)	
			2025	2050
Northeast	4.87	0.073	6.40	8.23
Appalachia	5.84	0.292	11.97	19.27
Corn Belt	5.98	0.179	9.75	14.23
Lake States	4.8	0.072	6.31	8.11
Southeast	5.49	0.275	11.25	18.12
Southern Plains	4.3	0.215	8.82	14.19
Northern Plains	3.47	0.052	4.56	5.86

As part of this analysis's focus on where we can go with biofuels as opposed to where we are now, we have asked, based on the success of breeding programs for switchgrass, corn, and other grasses, how much can we increase the yield of switchgrass? Based on the most comprehensive analysis to date examining future gains in switchgrass productivity, the answer is that by 2025, an aggressive breeding program could increase average yields to more than 8 dry tons per acre per year and by 2050, we could reach nearly 12.5 dry tons. And it is worth noting that these improvements could be achieved without using genetically modified plants.[22]

This level of gain assumes that annual switchgrass yields increase by slightly more than 0.16 dry ton per acre per year on average. This level of linear improvement in yields has been achieved by switchgrass, corn, and other grass breeding programs. Existing switchgrass breeding programs have improved yields by 0.05 to 0.29 dry tons per acre per year annually. Other grasses such as bermudagrass and Pensacola bahagrass have increased yields by two fold and seven fold in less time than we are assuming for switchgrass.[23] [24]

Corn breeding experience is also telling. Corn is actually a grass and is similar to switchgrass metabolically and in several other ways. Since modern breeding approaches began in the 1930s, corn yields have improved steadily from about 27 bushels per acre to more than 140 in 2003 for an annual rate of improvement of about 2.5 percent. These gains in corn grain yield have been paralleled by gains in whole plant biomass as harvested grain has remained a nearly constant 50 percent of the whole plant.[25] In addition to modern breeding techniques, corn has also benefited from modern fertilizers, pesticides, and herbicides. We will return to this point in a bit, but it is important to note that fertilizer, pesticide, and herbicide application rates have been going down relative to the tons of corn produced and that we expect to see the same trend in switchgrass—higher yields with more chemical treatment per acre, but less treatment per ton of biomass produced.

Given this history and the opinions of the experts participating in this project, reaching 12.5 dry tons per year by 2050 is eminently achievable based on steady application of current breeding methods. Furthermore, the theoretical maximum is about 22 dry tons per acre (similar to corn) and well above the 12.5 dry ton level, so with continued breeding programs and favorable economics, it is likely that improvements would continue well beyond 12.5 dry tons and that gains could be achieved faster.

These gains will be highly impacted by the regions and soils where switchgrass is planted, which in turn will be determined by the economics. For a given price for switchgrass, the land that can most economically produce switchgrass will be the first to convert. This involves a balancing act between the appropriateness of the land for switchgrass and the appropriateness of the land for other crops. Obviously the process of integrating biomass production with other demands such as animal feed protein also impacts this balance. Generally the best switchgrass lands—the Appalachian and Corn Belt regions—will be drawn into the market first, and then higher prices will draw in land that is less ideally suited. Figure 3 shows where and how intensively switchgrass would be grown in 2025 assuming that linear yield increases and a constant price of $40 per dry ton, but not factoring in integrations with animal feed protein production.[26] This map is offered here just to provide an indication of where switchgrass will be most competitive.

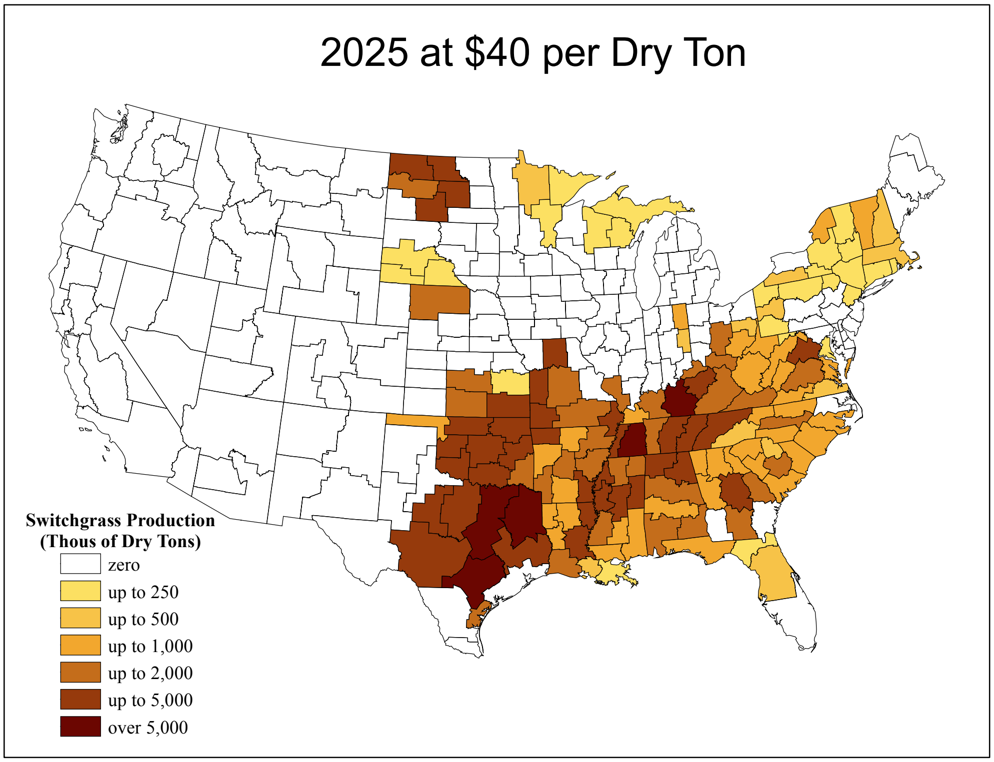


Figure 3. Map of Switchgrass Production in 2025 Assuming Constant Price of $40 per Dry Ton

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HOW SWITCHGRASS AFFECTS AIR, WATER, SOIL, AND HABITAT

Switchgrass is environmentally preferable to just about all traditional row crops cultivated today. Thus if we can meet some of the demands that these crops are currently meeting with switchgrass and thus enable switchgrass to replace millions of acres of traditional crops, there is the potential to dramatically reduce the environmental impacts of agriculture. Switchgrass's benefits stem in large part from its origins as a prairie grass native to the United States. Being native, it is better adapted to our climate and soil types, and wildlife is better adapted to it. Cultivating switchgrass would result in less water pollution and soil erosion and more soil carbon buildup and wildlife habitat than any of the major crops that it would displace.

On average, switchgrass requires less fertilizer, herbicide, insecticide, and fungicide per ton of biomass than corn, wheat, and soybeans. The difference in these levels is telling of both the amount of upstream energy and related pollution that different crops require, but it also gives insight into the sources of water pollution. When these chemicals are applied to crops they can either be absorbed by the plant or the soil or run off into groundwater supplies or nearby waterways.

Table 6. A Comparison of Energy Crop and Traditional Crop Chemical Application [27]

	Reduction relative to corn-wheat-soybean average
	Herbaceous perennial
Fertilizer	1.1-fold
Herbicide	6.8-fold
Insecticide	9.4-fold
Fungicide	3.9-fold

Modeling done for this report gives a clearer comparison of the level of actual runoff of nitrogen—one of the most important agriculture-related sources of water pollution.[28] Here we have modeled the level of nitrogen absorption for switchgrass, corn, and soybeans when all three crops are provided with more than ample supplies of the fertilizer. If we assume that these crops absorb the same amount of nitrogen when more typical amounts of fertilizer are applied, then the rest presumably ends up leaching into groundwater or running off into surface water. Because switchgrass is more effective at absorbing nitrogen, just under 10 kilograms per hectare per year of a typical application ends up as water pollution. This is less than one-eighth of the runoff from a hectare of corn and three-fifths of the runoff from soybeans. Table 7 summarizes these results. While applications of fertilizers have been becoming more strategic for traditional crops such as corn and soybeans, switchgrass is likely to benefit from these same techniques and thus should result in dramatically less water pollution due to agricultural fertilizer runoff for the foreseeable future.

Table 7. Runoff from Corn, Soybeans, and Switchgrass

	Typical N application (Kg/hectare/year)	Percent of typical N application that ends up in runoff	N Runoff (Kg/hectare/year
Corn	135	58%	78.8
Soybeans	20	81%	16.25
Switchgrass	50	19%	9.7

Because switchgrass is a perennial and has a much more extensive root structure than traditional row crops, cultivating switchgrass also results in dramatically less soil erosion. Previous analysis suggests that erosion from switchgrass is between 11 and 110 times less than corn and generally less than all other agricultural crops except for pasture and hay.[29] (See Table 8.) Modeling done for this report shows even greater differences in erosion, with switchgrass resulting in 0.9 ton/hectare/year of soil loss while corn and soybeans result in 67 and 109 tons/hectare/year respectively.

Table 8. Average Soil Erosion from Different Crops

Crop	**Erosion Losses (ton/ha/yr)**
Herbaceous energy crops—switchgrass	0.2 to 2
Maize (corn)	22
Other agricultural crops	14 to 41

Pasture and hay	0.2
Native forest after disturbance	2 to 17
Average native forest rotation	2 to 4
All short rotation woody crops	2 to 4

The cultivation and harvesting of any crop has air pollution impacts. These come from a range of sources including the harvesting equipment and volatilization of chemicals that are used to treat the soil. Air pollution is the one area where we can draw on extensive life cycle modeling to allow us to compare biofuels with the gasoline alternative. These results are presented below in the sections on producing biofuels and using them.

One aspect of air pollution that is important to mention in the context of growing switchgrass is its superior ability to sequester carbon in the soil, thus reducing substantially the already very low life cycle greenhouse gas emissions from cellulosic biofuels. The substantial root base of switchgrass and the fact that it is a perennial grass allow it to sequester much more carbon per year in the soil than other crops that either have a shallower root base, are tilled annually or both. Counter intuitively, the amount of soil carbon under switchgrass increases when the crop is harvested annually.[30] This has the added advantage of improving soil organic matter levels, which raises the interesting prospect that switchgrass could be rotated with soil-carbon depleting crops. For instance, switchgrass could be grown for 10 years followed by a number of years of corn or soybeans. Of course such practices would need to be studied extensively to understand the long-term soil carbon impacts and their overall sustainability. Figure 4 below shows how soil carbon levels improve over time under switchgrass depending on the condition of the soil before the switchgrass is planted.

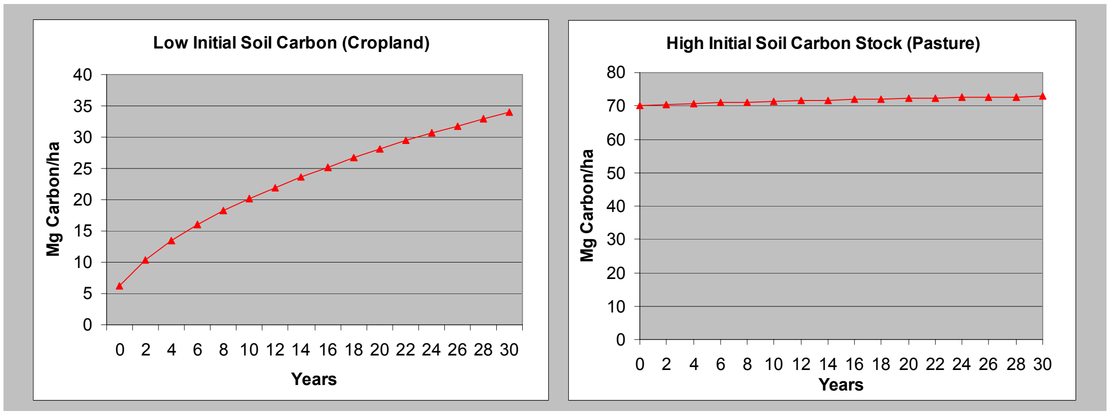


Figure 4. Switchgrass Improves Soil Carbon[31]

Finally, switchgrass is a native prairie grass and thus a good wildlife habitat. In particular, studies have been done looking at bird use of different crops. Switchgrass is currently usually harvested only once a year late in the fall to allow for most of the moisture and nutrients to leave the harvested portion of the plant, and this timing has the added advantage of allowing most nesting species to have migrated from the fields. To maximize the protein value of switchgrass, it would be harvested twice a year, in early summer and late fall. However, the first harvest would happen after most species have hatched their young. Table 9 below provides a comparison of both the number of birds and variety of different species spotted in switchgrass and other agricultural settings.

Furthermore, there are a range of crop management techniques that may be able to even further increase the habitability of switchgrass. For instance, leaving a buffer row around a field during harvesting can provide cover for animals during the winter. In areas where there are sensitive species, these measures should be pursued.

Table 9. Habitat Quality and Diversity for Different Crops[32]

Habitat Type[a]	Number of Breeding Pairs per 40 ha	Total Number of Breeding Species	Number of Sites Sampled
Dense switchgrass	182	10	8
Poor switchgrass	178	9	8
Reed canary grass[b]	246	9	6
Mixed warm-season grasses	126	13	7
Corn	32	5	16
Beans	22	2	9
a: Habitat types were categorized as follows: reed canary grass sites were not monotypes—they were fields where reed canary grass was the most common grass species (cover values ranged from 15% to 97%); dense switchgrass sites had >40% cover of switchgrass and <4% cover of other warm season grasses; poor switchgrass sites had <40% cover of switchgrass and <9% cover of other warm season grasses; mixed warm season grass sites had >72% cover of native warm season grasses other than switchgrass; bean and corn sites were on commercial bean (spy or snap) or corn fields, respectively.			
b: Reed canary grass ranked highest in bird density primarily due to the influence of the large number of red-winged blackbirds (*Agelaius phoeniceus L.*) that nest in it.			

Beyond the environmental impacts that occur on an acre by acre basis, when we start looking at biofuels producing more than 100 billion gallons a year, we need to consider the cumulative impacts of devoting that much land to dedicated energy crops. Fortunately there is enough diversity within switchgrass and other sources of cellulosic biomass and the economics of transporting biomass are such that we should be able to avoid developing unhealthy monoculturing near biorefineries.

There are different crops that might be grown as a dedicated source of cellulosic biomass, and even within the genus *Panicum virgatum* in which switchgrass falls there are many different varieties, some with major ecotypical and/or genetic differences. Taking advantage of this diversity will be important to reduce the spread of diseases and pests from both an environmental perspective and an economics perspective. The alternative—increasing application of chemicals—would start to reduce the environmental benefits of switchgrass.

Early on, when cellulosic biofuels plants are still moderately sized (e.g. requiring less than 5,000 tons per day), it is likely that the feedstock will be transported to the plant by truck. In this case, the economics will strongly favor having crops planted near the facility. The percent of land near a cellulosic biofuels plant that would need to be planted with an energy crop such as switchgrass depends on three factors: the tons per acre yield of the crop, the cost of transporting the crop from the field to the plant, and the size of the plant. We have already discussed the yield, which we expect to easily reach 12.5 dry tons per acre per year by 2050. As the crops have to be transported from farther away, the cost of transportation per ton goes up linearly. As we will discuss in more detail later, there are economies of scale to be gained from larger plants. In other words, a larger plant that might require feedstock from greater distances if excessively high densities are to be avoided is going to be less expensive. As a result, while the economics of truck based transportation will always favor higher density near the plant to reduce transportation costs, larger plant sizes will almost always justify the extra cost of transportation.

For plants requiring more than 5,000 tons of biomass per day, it is likely that the feedstock will be transported by train. While the logistics of supplying such large volumes of low-density biomass to a single site have not been demonstrated before, systems for doing so can easily be imagined. The key challenge is increasing the density before transportation, which can be achieved a number of ways. With train-based transportation, the crops can come from much farther away as the costs become a function of weight and density rather than distance. Thus for larger plants, there is little or no incentive for crops to be densely planted around the facility.

However, even if very large plants needed to get their feedstock from nearby, energy crops would still not need to be planted more densely than many of our crops are today. To meet the needs of plants using between 5,000 and 20,000 tons per day from within a 50-mile radius would require between roughly 3 percent and 11 percent of the land to be planted with a crop such as switchgrass. This may sound like a lot, but it is actually well below the national average of 19.2 percent of land in cropland.[33] This national average level of coverage would support a plant that took in more than 36,600 tons per day. Figure 5 shows the percent of land covered by croplands at the county level across the United States. As can be seen, there are plenty of counties with 75 percent or more of the land covered by cropland.

Table 10. Land Coverage Required to Serve Different Size Plants

		Plant size (tons/day)				
		500	1,000	5,000	10,000	20,000
Feedstock collection radius (miles)	10	6.5%	13.1%	65.5%	131.0%	261.9%
	20	1.6%	3.3%	16.4%	32.7%	65.5%
	30	0.7%	1.5%	7.3%	14.6%	29.1%
	40	0.4%	0.8%	4.1%	8.2%	16.4%
	50	0.3%	0.5%	2.6%	5.2%	10.5%
	60	0.2%	0.4%	1.8%	3.6%	7.3%
	70	0.1%	0.3%	1.3%	2.7%	5.3%
Assumes 12.5 tons/acre and that the plant operates at 90% capacity annually.						

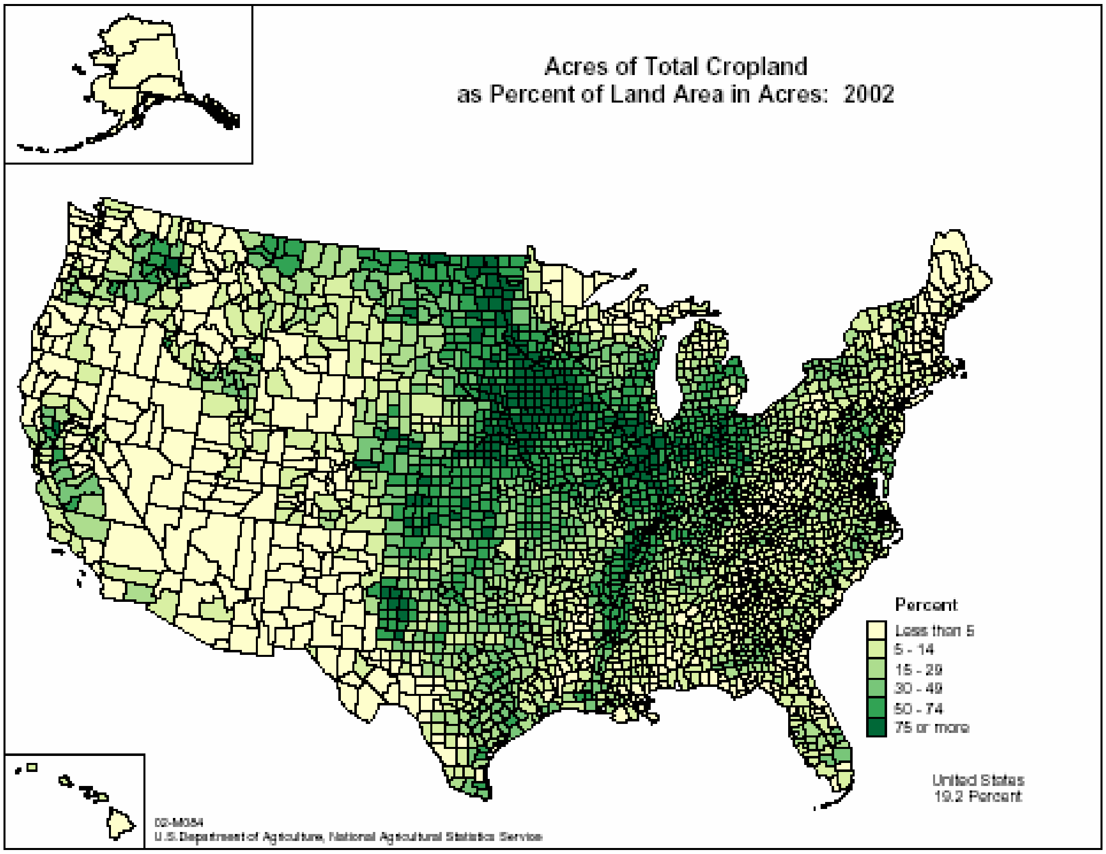


Figure 5. Percent of Land Covered by Cropland

Covering vast areas with one crop—monoculturing—presents an environmental and economic risk that should be avoided. However, by focusing on the potential to meet our biofuels needs on existing cropland and by improving yield, it is clear that even very large cellulosic biofuels plants would not require any increase in monoculturing, and if different varieties of dedicated cellulosic biomass crops, including different varieties of switchgrass, are used, then a shift from traditional crops to energy crops would greatly enhance habitat quality and diversity compared to the status quo. In any performance based policy, credit should be given for crop diversity and habitat management practices.

IS THERE ENOUGH LAND TO GROW BIOFUELS?

There is no simple answer to this question. It’s easy to paint a picture in which biofuels can provide only a small fraction of our transportation energy needs because of land constraints. Here, however, we’re focused on finding out what the potential for biofuels could be if we are serious about reducing our oil dependence. In this context, we believe that there are packages of innovations and changes to the way things are done that would allow biofuels to provide the vast majority of our total vehicle energy needs on land that is already under cultivation while still meeting our food and textile needs. Working through an example helps to illustrate this point. Consider the production of cellulosic ethanol with the goal of replacing all of our transportation related gasoline demand by 2050.

So how much gasoline do we need? Well, this too is a complicated question. Currently our cars and trucks use about 137 billion gallons of gasoline, 62 percent of our total transportation sector petroleum. But usage will change over time, depending on vehicle efficiency and how much people drive. More sprawl and a larger population will drive energy demand up, but smart growth policies could limit this growth or reduce it. Bigger and less efficient vehicles will drive up energy demand, but using more efficient technologies like hybrids could limit this growth or reduce it. Assuming no improvement in vehicle efficiency and continued growth in driving, by 2050, the United States could be using nearly 289 billion gallons of gasoline per year for transportation.

How much land would we need to meet that level of light-duty vehicle energy demand with cellulosic ethanol? With status quo switchgrass yields at 5 dry tons/acre/year and currently achievable cellulose-to-ethanol conversion efficiency of about 50 gallons per ton (the equivalent of 33 gallons of gasoline), about 1,750 million acres would be required to meet projected 2050 light-duty gasoline demand. In comparison, the area of the contiguous 48 states is about 1.9 billion acres, U.S. cropland and rangeland is about 700 million acres, and U.S. cropland is about 400 million acres, and the only land on which switchgrass is growing now is part of about 30 million acres of Conservation Resource Program land. The conclusion based on the status quo can only be that cellulosic biofuels would be bit players.

But if we’re serious about overcoming oil dependency, we have to innovate and change. We know that we can improve the fuel efficiency of our cars to more than 50 miles per gallon. Implementing this technology for our cars and trucks between now and 2050 would reduce our gasoline demand to less than 150 billion gallons a year. Smart growth polices would help reduce the distances we need to drive and allow more people walk and use mass transit. These policies could reduce our demand further to about 108 billion gallons per year in 2050. To meet this level of demand with our current cellulosic ethanol technology, we would still need nearly 660 million acres. This is still a lot.

We’ll also innovate and change the way we make biofuels. For example, our analysis provides support for R&D-driven advances that could result in a conversion efficiency of about 105 gallons of ethanol per ton of switchgrass (the equivalent of 69 gallons of gasoline). This step alone would reduce our land requirement to about 313 million acres. By combining the biological conversion process that produces cellulosic ethanol with thermochemical conversion processes that can produce additional biofuels such as Fischer Tropsch diesel and gasoline, we can effectively raise the conversion efficiency to the equivalent of 77 gallons of gasoline and 11 gallons of diesel per dry ton of biomass. Just using the gasoline portion of this gets us down to nearly 280 million acres. At least this is less land than we currently use for crops, but it is still too much.

Another innovation that’s expected is a 50 percent increase in the yield of switchgrass. As discussed earlier, an average annual increase across the country of about 0.16 dry ton per acre should be achievable and sustainable through 2050. This would increase yields from 5 tons/acre/year to about 12.4 tons by 2050. This is not close to the maximum yield from switchgrass. Improved yield through 2050 cuts the amount of land more than in half, to 114 million acres.

Having reduced our land requirement to provide all of our gasoline needs in 2050 from 1,750 million acres to 114 million acres, if we can find ways to integrate biomass production with our current agricultural demands, we are within striking distance. Between now and 2050, we can safely assume that if there is a market for non-nutritive cellulosic biomass, farmers will incorporate any innovations that increase their profits. One of the innovations discussed later in this report is the ability to extract animal feed from switchgrass. (See *Coproducing ethanol and animal feed protein* for further discussion.) Currently about 73 million acres are used to grow soybeans primarily for animal feed and vegetable oil. This means that switchgrass could provide a sizable chunk of the profits that soybeans currently provide farmers. If soybean farmers converted all their acres to switchgrass we would need about 41 million acres. If only half converted we would need 77 million acres.

There is another way that farmers will almost certainly adjust to a market for cellulosic biomass. Those farmers who produce residues that contain cellulose will find ways to collect them. For instance, corn farmers currently leave almost as much biomass on the fields as they collect. What they collect is primarily corn kernels. What they leave behind—corn stover—has a high cellulose content. Some of this is needed to reduce soil erosion and fertilizer requirements, but recent analysis suggests that as much as 90 percent of the stover could be collected if all corn were grown using no-till practices.[34] If corn is grown in rotation with switchgrass, it is possible that very high proportions of stover could be removed while maintaining soil carbon levels. Similar strategies might be employed for other cereal crops such as wheat and oats. For our purposes, let’s assume 75 percent stover collection. This amounts to more than 240 million tons or the equivalent of nearly 20 million acres of switchgrass. If we’re using all of the soybean acres, then we still need 21 million acres. If we are using only half the soybean acres, then we need 58 million acres.

Recall that about 30 million acres of cropland is currently in the Conservation Reserve Program. While the primary purpose of this program is erosion control, which will be well served by growing perennial energy crops, not all of this land can be used. The CRP also serves to protect sensitive landscapes and habitats. Past analysis has suggested that between one-third and one-half of this could be used depending on the management priorities.[35]

This leaves us needing between 6 and 48 million acres to meet all of our potential transportation gasoline demand in 2050. If we stop here, we can produce between 58 and 94 percent of all our transportation gasoline needs in 2050. And let’s not lose track of the Fischer Tropsch diesel we would also be producing. If we can get to 100 percent of our gasoline demand and we apply some of the same fuel efficiency efforts to diesel-burning vehicles, then we would meet 17 percent of our diesel demand in 2050.[36]

Greater than average improvements in switchgrass yields could easily bring us to zero new acres if we can use all of the soybean acres. All that would be needed is an additional increase of 0.7 ton per acre over 46 years. There are also other innovations that farms might incorporate, such as collecting other types of agricultural residues, growing winter cover crops between summer-grown annual crops, cultivating hay on underutilized pastureland, and using the same innovations that enable low-cost biomass processing to increase feed digestibility.

Most if not all of the strategies we have described for integrating production of cellulosic feedstocks into existing agricultural practices would bring more value per acre to farmers and would be favored by market forces. In the face of a large new market demand for cellulosic biomass, farmers will rethink what they plant and how they manage their land. It is very likely that strategies that cannot be envisioned today to coproduce cellulosic biomass will be conceived in response to this opportunity. In light of the inherent properties of cellulosic crops, including increases in soil carbon, we are optimistic that most such strategies will be beneficial to the environment, although appropriate regulations will be needed to ensure this result. At the same time, there are also likely to be other new demands on our agricultural land. For instance, there is growing interest in using agricultural residues or new crops to replace forest products including paper, and of course there is also our heavy-duty vehicle energy demand.

Table 11. How Much Land to Meet Gasoline Energy Needs in 2050?

	Gasoline Demand (billions gals of gas equiv)	Switchgrass Yield (dt/acre/yr)	Conversion Efficiency (Gals gas equiv/dry ton)	Land needed to meet gasoline demand (millions of acres)	
Production and efficiency gains					
Status quo in 2050	289	5	33	1753	
Smart growth and efficiency by 2050	108	5	33	657	
Increase conversion efficiency	108	5	69	313	
Biofuels coproduction	108	5	77	282	
Increased switchgrass yield by 2050	108	12.4	77	114	
Alternative sources of land and biomass				Aggressive Integration	Partial Integration
Protein recovery	73 million acres of soybeans, 50% to 100% conversion to switchgrass			41	77
Corn stover	323 million tons of corn stover, 75% collected for biofuels			21	58
CRP land	30 million acres, 33% to 50% conversion to switchgrass			6	48

How much of our future transportation energy needs will we be able to get from biofuels supplied from our current croplands? There is no way for us to definitively answer the question. However, the math we have just gone through suggests that we could get a very substantial amount, and we might well be able to provide all our gasoline needs and an important part of our diesel needs. The one answer we can provide definitively is that if we're serious about reducing oil dependency, we have plenty of land for biofuels to make a tremendous contribution.

CHAPTER 4

WHAT PROCESSING BIOFUELS LOOKS LIKE

After growing a supply of cellulosic biomass, we have to convert it into a form of energy that we can readily use. Processing biomass is comparable to refining oil into fuel; it converts cellulosic plant matter into a viable fuel for cars and trucks, and just like refining, it is possible to make more than one product at a time. There are a variety of ways to process biomass. This chapter reviews two of the most promising methods—biological and thermochemical processing—and their environmental impacts and looks at the potential to produce animal feed protein at the same time as we produce fuels and power.

Both processing technologies face the same broad challenge: turning cellulosic biomass into reactive intermediates that can then be converted into readily usable forms of energy. Cellulose biomass is competitively priced with oil. At $40 per dry ton, the raw energy value of cellulosic biomass has the same value as oil at $15 per barrel. Recent oil prices of about $50/barrel are the equivalent of switchgrass at $135/dry ton.[37] Thus, the key technical hurdle to be surmounted is the cost of processing rather than the cost of feedstock. Process design studies consistently indicate that steps associated with overcoming the recalcitrance of cellulosic biomass—whether by pretreatment and enzymatic or microbial hydrolysis, acid hydrolysis, or gasification—are the most costly and involve the greatest technical risk, but fortunately they also have the largest potential for R&D-driven cost reduction. Given the value of the energy in biomass, were it not for the limitations of current technologies in overcoming the recalcitrance of cellulosic biomass, bioenergy production would be much more widespread than it is today.

BIOLOGICAL CONVERSION

The options for biological processing of cellulosic biomass considered here all involve fermentation of carbohydrates to ethanol by microorganisms. Different options are distinguished based on how fermentable carbohydrate is produced. Production of fermentable carbohydrates in the form of soluble sugars can be accomplished by acid hydrolysis at either high concentration and low temperature, or low concentration and high temperature. Alternatively, biomass can be pretreated to make the carbohydrate component accessible to subsequent biological processing. Pretreated biomass can be hydrolyzed by enzymes to produce sugars which are then fermented, or it can be fermented directly by cellulolytic microorganisms without added enzymes. The latter approach is referred to as consolidated bioprocessing (CBP).

Among processes featuring pretreatment, there are several alternative approaches. Prominent pretreatment options involve use of dilute (or very dilute) acid, hot water, lime, and ammonia. None of these pretreatment technologies are entirely mature, and thus definitive cost and performance comparisons are not possible. We have assumed ammonia pretreatment because it is particularly compatible with protein recovery, one of the main feedstock co-utilization strategies considered here, and also because it has desirable features in terms of not inhibiting fermentation, not degrading carbohydrate, and operating under mild conditions.

The cost of biological processing involving acid hydrolysis is roughly comparable to that using pretreatment followed by enzymatic or microbial hydrolysis based on current technology. However, pretreatment-based processes are widely thought to have potential for substantially lower costs in the future due to foreseeable R&D-driven advances. In the context of mature technology, the experts in biological processing involved in this project, as well as others, believe that CBP featuring microbial conversion without added enzymes can be developed into the lowest-cost commercially mature option within 10 years with a concerted R&D, demonstration, deployment effort. Thus the mature technology scenarios in this study are based on consolidated bioprocessing.

Development of CBP-enabling microorganisms involves combining in one microorganism features already possessed by individual microorganisms, which is the essence of recombinant DNA technology. There is strong evidence supporting the technical feasibility of combining the features needed to enable CBP.[38] While such development represents an ambitious biotechnological goal, successful organism development involving similarly ambitious goals is being reported with increasing frequency in the pharmaceutical industry.[39]

THERMOCHEMICAL CONVERSION

Burning biomass is a form of thermochemical conversion, but it produces only one useful product: heat. The heat can be captured in the form of steam and used for a variety of purposes including producing electricity. Direct combustion followed by steam based power generation is known as Rankine cycle power generation. Rankine cycle equipment is commercially mature, but it is not the most efficient way to extract energy from biomass, and it cannot produce motor vehicle fuels.[40] We include Rankine cycle power production in our analysis, but the technology advances that are most important from a mature technology basis are those that will lead to higher efficiencies and a broader range of products, and this requires gasification.

When gasified, biomass is reduced to a mix of hydrogen, carbon monoxide, hydrocarbons, and carbon dioxide. This mixture is known as synthesis gas, or simply syngas, and can be burned for energy, in a high-efficiency gas turbine combined cycle for example, refined to make hydrogen, or used to synthesize a host of products including chemicals and fuels. Combined cycle technology and synthesis reactors are commercially established technologies today for use with natural gas and, to a lesser extent, synthesis gas made from coal. With little further development these “downstream” technologies can be commercially ready for use in biomass thermochemical conversion systems. Thus the challenges lie in overcoming the recalcitrance of biomass—in this case through the gasification process.

In our analysis, we assume that the three main, remaining challenges to biomass gasification have been overcome. These challenges are being able to use a pressurized, oxygen-blown gasification process, being able to feed biomass into a pressurized gasifier, and being able to clean up the raw synthesis gas to meet the specifications of downstream equipment. A modest level of laboratory R&D, coupled with successful pilot-scale demonstrations that establish commercial feasibility, are needed in these areas.

Pressurized, oxygen-blown gasification is the most efficient way to provide a pressurized syngas with a high energy content. Combined cycle power generation and synthesis of biofuels benefit from availability of a pressurized gas with as high an energy content as possible. It will be more energy-efficient to generate a pressurized gas by operating a gasifier at pressure than by generating the gas at low pressure and then compressing it to higher pressure. Also, using oxygen for gasification will provide a much higher energy-content gas compared to using air, since there is no nitrogen dilution when oxygen is used. Pressurized air-blown gasification can be used for modest-scale combined cycle power generation, but pressurized oxygen-blown gasification is preferred from performance and cost perspectives for fuels production,[41] as well as for any application of gasification at a larger scale.[42]A knowledge base relating to pressurized oxygen-blown gasification exists, but some modest additional pilot-scale efforts would be required to demonstrate commercial feasibility of today's pressurized oxygen-gasification technologies.[43]

In terms of feeding biomass into a high pressure (> 20 atmospheres) gasifier, commercial technologies exist today, but the available feeder technologies (e.g., lock-hoppers) penalize overall plant performance because of high consumption of inert pressurizing gas and the associated gas compression work required. Some efforts have been made to develop feeder systems that would considerably reduce the consumption of inert gas without significant added cost (e.g., plug or piston-feed systems), but some additional effort is needed to demonstrate the commercial feasibility of such technologies.[44]

The extent to which impurities must be removed from syngas depends on the intended subsequent use of the gas. Burning the gas directly in a boiler requires a relatively low level of gas cleanup that can be easily achieved with existing technology. Burning the gas in a gas turbine combined cycle requires a greater level of gas cleanup. Catalytic conversion of the synthesis gas into fuels requires a very high degree of gas cleanup. In our analysis, we have assumed "hot gas cleanup" of alkali species for combined cycle gas turbine (CCGT) power production and catalytic tar and oil cracking for the synthesis of biofuels. "Hot gas cleanup," which requires keeping the syngas at or above 350°C until it is delivered to the gas turbine combustor in a CCGT, was successfully demonstrated in Sweden in the 1990s at pilot-plant scale in a gas turbine combined cycle application.[45] Catalytic cracking of the tars and oils in syngas should be able to achieve a 99 percent reduction of these heavy hydrocarbons, making the energy they contain available as syngas and protecting biofuels synthesis equipment.[46] However, more R&D and piloting work is needed to bring such technology to commercial readiness.

PRODUCING BIOFUELS ALONG WITH OTHER PRODUCTS

As can be seen from the eight product configurations we are assessing, we are primarily concerned with using the biological and thermochemical processes to produce multiple products simultaneously. We have already seen how using crops to produce different biofuels and animal feed protein simultaneously allows for much greater land-use efficiency. Compared to facilities making single products, coproduction can yield higher biomass conversion efficiency, and enable more effective use of invested capital, which can make all the difference in the economics of biofuels. The only single product production process we have analyzed is power and we have analyzed it in two stand alone configurations primarily for the purpose of understanding the tradeoffs involved in focusing on biofuels.

The corn ethanol industry already coproduces a number of products along with ethanol. For instance, most corn ethanol mills produce animal feed components. Some also produce corn syrup and CO_2 for beverages. In some instances these coproducts are actually the driving force behind the economics of the plant, with the amount of ethanol produced fluctuating based on the market price of the primary product. There is also a major effort under way to develop biocatalysts that convert the simple sugars in corn into a range of chemicals and products such as precursors to plastics and other polymers.

Cellulosic feedstock will probably be able to produce some of these same biologically derived products. However, one can easily imagine scenarios where corn is used to make higher-value, lower-volume products for which the low-cost feedstock is less important, and products for human consumption, while cellulosic biomass is used primarily for fuels. Recall that about 40 percent of the energy in cellulosic biomass is in the form of lignin, which is not biodegradable. Taking advantage of this energy requires larger facilities and is generally going to favor large-volume products such as fuel and electricity.

The animal feed protein coproduct referred to in the fourth configuration above comes not out of the back end of cellulosic biofuel facility but from the front end. Though a pretreatment process, it should be possible to separate leaf protein that would be very suitable for animal feed. This coproduct is especially important not only because of its financial value—it is potentially worth around $0.13 per gallon of cellulosic ethanol—but also for the land that it potentially makes available for conversion to switchgrass. We currently use about 73 million acres to grow soybeans primarily for animal feed protein and also for vegetable oil. While switchgrass cannot be used to produce vegetable oil, if it can provide a similar financial value to growers and a similar product to meet our animal feed protein needs, then we may be able to convert much of the soybean acreage to switchgrass. Obviously if we convert all of the land then we will need to import our vegetable oil, but this may not be an insurmountable obstacle as there are crops that grow better in other parts of the world that produce much more oil per acre.[47]

COPRODUCING ETHANOL AND ANIMAL FEED PROTEIN

Coproducing animal feed in the form of protein as part of the production of biofuels has the potential to dramatically improve the economics of biofuels production, increase farmer income, and allow the acres currently used to grow animal feed protein to do double duty. Because the protein extraction processes takes place in a liquid setting, it is more easily integrated with biological process, which are also liquid-based, than thermochemical processes, which generally perform better with dry biomass. Recovery of animal feed protein should also integrate fairly easily with the pretreatment step needed for biological processes.[48]

How much might protein recovery improve the economics of biorefining to ethanol? Since 1980, the price of soymeal has ranged between \$0.14 and \$0.28 per pound, with an average price around \$0.20 per pound. Our analysis of the technologies for recovering protein from switchgrass suggests that it would be done in two stages with about 75 percent of the protein being recovered in the first at a higher quality and the remainder being recovered in the second slightly degraded. Assuming the first stage is valued at \$.20 per pound and the second at \$0.15, recovering protein from a cellulosic ethanol plant could lower the cost of ethanol by \$0.11 to \$0.13 per gallon, depending on the size of the facility.[49] Importantly, even at the smaller end of the scale of facilities that we have analyzed and at the historic low price for soymeal, recovering protein still pays for itself.

The protein for animal feed in switchgrass is known as leaf protein. It is protein found in the leaves and stems of green plants. Grass hays including switchgrass contain about 10 percent protein on a dry weight basis. Crop residues such as corn stover, rice straw, and wheat straw contain approximately 4 to 6 percent protein, and high-quality forages like alfalfa and alfalfa-grass mixtures can have 15 to 20 percent protein.[50]

Leaf protein recovery for human food has been a research topic since the 1940s. Most of what we know about leaf protein recovery is due to this research.[51] However, leaf protein recovery as an animal feed in the context of biofuels and chemicals has a much shorter history, and much less research has been done. Nonetheless, there are many reasons to be optimistic about the potential.

Biological conversion of grasses and crop residues to ethanol requires converting most of the initial plant into water soluble components to get access to the sugars. In the process, the protein will tend to be released from the plant matrix. We have well-established technologies such as membrane filtration to recover soluble proteins from water. Initial research confirms that 60 to 80 percent of protein can be extracted from crop residues and grasses using warm, slightly alkaline water.[52]

Animal feed proteins are valued primarily on the basis of their content of essential amino acids, particularly the "limiting" amino acids, those required for animal function but in shortest supply in a particular feed. Depending on the animal class (poultry, swine, cattle, etc.), the limiting amino acids in soybean meal tend to be lysine, tryptophan, cystine and methionine, histidine, valine, and threonine. While the data are less abundant for the amino acid composition of grasses and crop residues, Table 12 shows the values for 48 percent protein soymeal and average values of different sources for an equivalent 48 percent recovered grass or crop residue protein meal.[53] Leaf protein is roughly comparable to soymeal protein in many limiting amino acids, and definitely superior in others. Indeed, considerable research has shown that leaf protein has a biological value greater than that of soybeans but less than that of milk.[54]

Table 12. Comparison of Soymeal and Grass/Crop Residue Protein Meal

Amino Acids	Percent by Weight	
	48% Protein Soymeal	48% Grass/Crop Residue Protein Meal
Lysine	6.5	5.8
Tryptophan	1.5	3.4
Cystine + Methionine	3.1	3.0
Histidine	2.8	2.3
Valine	4.9	6.6
Threonine	3.9	5.8

Animal feeders are very cautious about changing feeds, and many more animal feed trials would need to be done before recovered leaf protein would gain wide acceptance, but animal feeding to produce meat, milk, and eggs is also an extremely competitive commodity business. Approximately 70 percent of the cost to produce these animal commodities is determined by the costs of feed. Therefore, producers have a huge incentive to use new feed ingredients if these ingredients are competitively priced and nutritionally adequate for the task.

If the case for recovered leaf protein is so strong, why isn't it being done already? First animal feeders must be convinced through feeding trials that the leaf protein products will perform as desired, and they are unlikely to pay for such trials. Furthermore, the technology to produce these leaf protein products in a biorefinery system must be better developed. While neither of these tasks is particularly difficult to conceive or execute, the necessary research and development must be planned, reviewed, funded, done, and made available to users. Second, even if leaf protein could be recovered today, there would still be the question of what do with the cellulose-rich residue left over after the protein is extracted, as there is currently no market for this residue. Protein recovery can improve the economics and environmental impacts of cellulosic ethanol, but the reverse is true too.

AIR, WATER, AND WASTE POLLUTION FROM PRODUCING BIOFUELS

Recognizing that to produce more than 100 billion gallons of biofuels the United States would need to build hundreds of biorefineries, it is important to understand the local impacts that these facilities will have. The three types of environmental impact that are of most potential concern in the production of biofuels are air, water, and waste. Of course these facilities need to be sited carefully to avoid land, use and habitat impacts, but these facilities do not use a particularly large amount of land nor is there any reason that they need to be sited in sensitive landscapes. After careful review of the literature and consultation with experts, NRDC and UCS have concluded that there is no reason that biorefineries using biological, thermochemical, or combined biological and thermochemical processes should have unacceptable pollution impacts if appropriate regulations and control technologies are adopted.

As discussed earlier, we primarily address air impacts on a life cycle basis in our comparative assessment of our eight different product packages. In this section we will focus only on the air pollutants emitted from biorefineries that are of greatest local impact—nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon monoxide (CO), and particulates. For all of these pollutants, biorefinery emissions should be either inherently low or controllable.

Biological processing to make cellulosic ethanol can produce significant quantities of VOC and particulates. The particulates are primarily fine dust that results from feedstock handling and are difficult but not impossible to control by doing more handling inside and using water to keep the dust down. The evaporative emissions are largely caused by the mixing of ethanol with gasoline, which is required by law to make the ethanol undrinkable, and again can be controlled by doing the mixing where the VOCs can be collected and treated.

By comparison, corn ethanol plants face a much larger air pollution challenge because they rely primarily on the on-site combustion of fossil fuels—most often coal—for energy to drive the ethanol processing. This results in significant emissions of SO_x, NO_x, CO, mercury, particulates and CO_2. It is worth noting that some early corn ethanol plants had severe VOC air pollution problems, but these have largely been resolved through proper sizing of pollution control devices.

In contrast, biological processing draws its process energy from the thermochemical conversion of the non-carbohydrate portion of the biomass. During the early stages of development, it is likely that this non-carbohydrate portion will simply be burned with the energy captured through Rakine cycle steam boilers and turbines. This direct combustion can result in significant quantities of NO_x, CO, and particulates. However, traditional power plant emissions control technology should be able to reduce these emissions to acceptable levels.

Over time, it is likely that biological processing will be paired with gasification. The air pollution impacts of gasification come almost entirely from the combustion of the syngas. The local air impacts of syngas combustion for power are very similar to those from the combustion of natural gas. Sulfur and hazardous air pollutants are harmful to the advance turbines used with gasifiers, so these are removed from the syngas before combustion. The local air pollutants formed during syngas combustion are NO_x, CO, and some VOC. Again, these can be reduced substantially through pollution controls, and given their generally lower starting point, the resulting emissions can be extremely low. Production of Fischer Tropsch fuels or DME is also gasification-based, and there are minimal local air impacts from these processes.

Water and waste impacts should also be very low with proper regulations and control devices. Biological processing results in significant levels of soluble organics that, if released with wastewater without being properly treated can put a significant oxygen demand on waterways. Fortunately standard waste water treatment technologies can virtually eliminate this problem.[55] In the context of our mature processes, all of these materials are treated first in an anaerobic digester to capture methane gas that is then fed into the gasification process. The anaerobic digestion has the added advantage of enabling much higher water recycling within the facility by removing compounds that would otherwise prohibit water reuse. About 95 percent of the treated water is recycled, and the rest (about 280 gallons per minute for a 5,000 dry ton per day plant) is treated again before being released. This two-step process with high levels of water recycling is consistent with current practice in recently constructed corn processing plants and allows the processes we have analyzed to produce no untreated wastewater. Proper regulations will be necessary to ensure proper water treatment, but in our analysis the water treatment was done primarily for the energy value of the methane captured. In other words, the economics encourage good environmental practices.

The high level of water recycling also allows us to minimize the total amount of fresh water used. Approximately 2 kg water per kg dry biomass feedstock—about 1,700 gallons per minute—are required as make-up water to account for the treated discharge as well as water consumed during hydrolysis or lost to evaporation. Petroleum refineries, by comparison, typically use 1.8 to 2.5 kg process water per kg crude feedstock—4,400 to 6,200 gallons per minute for a 100,000 barrel per day refinery—and discharge between 1.7 and 3.1 times as much water.[56]

The only water pollutant of concern from the thermochemical process is waste heat. Traditionally boilers and other power plants located near bodies of water have used a once-through cooling system, drawing cool water and returning heated water. The water intake can damage fish and the heated water can destroy habitat. The alternatives are known as wet or dry cooling systems. Wet system use water evaporation to remove excess heat. Dry systems primarily use air.

In addition to the biosolids resulting from waste water treatment, the only solid waste that our combined biological and thermochemical processes will need to dispose of is the ash content in the cellulosic biomass. This material, which makes up about 4 percent of the weight of dry feedstock, will not break down in either processes.[57] While the ash and biosolids can be disposed of with little anticipated difficulty, we suspect that uses for these products would be found in a mature, large-scale biorefining industry.

In the petroleum industry, for example, only a minor fraction of crude oil was utilized by early refineries with the remainder being treated as waste. However, modern refineries convert nearly 100 percent of the mass of petroleum taken in by the plant into salable products. When asphalt first was produced in oil refining, for example, there was little demand for it. Today, we use it as a road surface. Similarly, we think it likely that biosolids resulting from the biorefineries we envision could be used as a soil additive, and ash might be incorporated into concrete aggregate or other products. If protein is not recovered and sold as we have discussed, it should be possible to recover a high fraction of the feedstock nitrogen as ammonia fertilizer, as is currently done by coal refineries in South Africa. Recycling ammonia to the fields where bioenergy feedstocks are grown offers substantial benefits in terms of both cost and life cycle energy inputs in light of the energy-intensive nature of ammonia manufacture. In general, we see these and other integration strategies as natural outgrowths of the evolution of a mature biomass refining industry. Thus, while we believe appropriate regulations are essential to ensure careful management of "waste" flows and other environmental aspects associated with biomass refining, it is appropriate to recognize that such refining offers opportunities for multiple environmental benefits at many levels and that many of these benefits will be driven by the economics of the processes.

GENETICALLY MODIFIED ORGANISMS AND BIOLOGICAL PROCESSING

As discussed in the context of biological processing and, in particular, consolidated bioprocessing, genetically modified industrial microorganisms (GMIM) are almost certain to be central to enabling fermentation of the carbohydrates in cellulosic biomass. This type of use of GMIM should be distinguished from the use of genetically modified crops (GMC). While the tools used to develop both GMIM and GMC are similar, the context for their use is very different. The GMIM used to break down and ferment cellulosic biomass would be specifically designed to thrive under manufactured conditions, such as high temperatures. Unlike GMC, which are designed to thrive in nature, the GMIM designed to make cellulosic biofuels (or chemicals for that mater) would be at a distinct competitive disadvantage in the wild.

Of course, testing and appropriate regulatory safeguards are needed—and possible—to ensure that biofuels GMIM do not pose a threat. However it is telling of the smaller inherent risk posed by GMIM as opposed to GMC that the Green Party in Germany, long opposed to the use of genetically modified organisms, has endorsed the use of GMIM while maintaining their opposition to GMC.

PROPOSED AND EXISTING PROJECTS

Although there are no commercial biomass Fischer Tropsch facilities in operation, there are fully commercial facilities that turn coal into Fischer Tropsch fuel using a process very similar to that which would be used for biomass. Furthermore the process of making Fischer Tropsch fuels out of syngas is also used commercially. Coal-to-Fischer Tropsch fuel plants have been operating in South Africa for five decades, a facility is under construction in China, and another has been proposed in Pennsylvania. In Europe, one facility, operated by ECN Biomass and Shell in the Netherlands, has successfully produced Fischer Tropsch diesel (FTD) from willow during two trial runs of 150 and 500 hours.[58] Another facility, operated by the German company CHOREN, working with DaimlerChrysler and Volkswagen, has made progress in producing FTD from wood and biomass waste products.[59]

Five cellulosic ethanol plants have been proposed over the last ten years or so for the United States, but none have been built. A demonstration-scale plant has been built in Canada, and the company that developed this plant, Iogen, is proposing to build another. All of these plants are summarized in Table 13.

Of the five plants proposed in the United States, two were proposed by Arkenol, both for California and both using concentrated acid hydrolysis. These plans are indefinitely on hold while Arkenol is developing a plant in Japan with aid from the Japanese government. Another of the five plants was proposed by Masada for New York. This plant would also use concentrated hydrolysis. Masada is still actively trying to develop this plant. The remaining two plants were proposed by BC International (BCI). These would be dilute acid hydrolysis plants. One was proposed for Louisiana and the other for California. BCI is still actively working to develop the Louisiana plant and hopes to start permitting and construction as soon as next year.

Table 13. Proposed and Developed Cellulosic Ethanol Plants

Developer	Site Location	Feedstock	Technology
Arkenol	Sacramento, CA	Rice straw & other agricultural residues	Concentrated acid hydrolysis
Arkenol	Orange, CA	Rice straw & other agricultural residues	Concentrated acid hydrolysis
BCI	Jennings, LA	Sugarcane bagasse	Dilute acid hydrolysis
BCI	Gridley, CA	Rice straw/Wood waste	Dilute acid hydrolysis
Iogen	Ottawa, Canada	Wheat, oat, and barley straw	SSCF enzyme hydrolysis
Iogen	-NA-	-NA-	SSCF enzyme hydrolysis
Masada	Middletown, NY	MSW cellulosic biomass	Concentrated acid hydrolysis

The only plant actually in operation is the demonstration-scale plant built in Ottawa, Canada by Iogen. This plant uses an enzymatic process known as simultaneous saccharification and co-fermentation, which is a step in the evolution towards CBP but does not provide all the cost-reduction benefits promised by CBP. The company has announced plans to build a larger commercial-scale plant that would produce 52 million gallons of ethanol a year and would cost about $250 million to build, but Iogen has not said where it will build the plant.

CHAPTER 5

WHAT USING BIOFUELS LOOKS LIKE

After growing plants and turning them into fuels, the last step is to use the fuel. This includes distributing it, storing it, and burning it in our cars and trucks. From a technical perspective, one of the attractive features of ethanol and Fischer Tropsch fuels is that they can be used with today's combustion engine technologies. However, we are also interested in how these fuels will perform in the vehicles of the future. Here the technological advances that we have analyzed take two forms: improved fuel efficiency and improved emissions control systems.

The Fischer Tropsch fuels are similar to their petroleum counterparts, but they have less sulfur, toxics, and other pollution precursors. Although there are air pollution impacts from the existing fleet as discussed below, technically all light-duty vehicles can already use up to 10 percent ethanol. In fact, virtually all of the ethanol currently produced is blended with gasoline and used in unmodified gasoline cars and light trucks. In addition, since 1998, the auto manufacturers have had an incentive to sell so-called flex-fuel vehicles that can run on virtually any mixture of gasoline and ethanol ranging from pure gasoline to E85 (15 percent gasoline and 85 percent ethanol). As a result there are about 1.2 million vehicles on the road today that have this flexible fuel capability.[60] Unfortunately, since they are not required to run on high ethanol blends, almost all these vehicles run on gasoline; as a result, the FFV credit program has actually increased the consumption of gasoline in the United States. Of course, ethanol fueling stations are extremely limited, and E85 is expensive. Moreover, most drivers are unaware that their flex-fuel vehicles have this capability. As a result, less than 0.25 percent of all ethanol is used in high concentration mixes.[61] Taken together, however, these two potential uses—primarily the potential to provide 10 percent for traditional vehicles' gasoline demand but also the potential to provide 85 percent of the existing flex-fuel vehicles' gasoline demand—represent a potential market of more than 16 billion gallons of gasoline demand per year.[62]

Dimethyl ether (DME) is not as easy to use. To be kept as a liquid, the fuel must be stored under mild pressure, like liquid petroleum gas. This lower-pressure storage does not pose the technical challenges that face a light gas, such as hydrogen or even natural gas, but using DME would require significant infrastructure changes as both vehicles and fueling stations would need to be modified to deal with a pressurized fuel. For this reason, we have limited our analysis of DME to our life cycle impact analysis and do not discuss it in further detail here.

IMPROVEMENTS IN FUEL EFFICIENCY

New vehicle fuel economy is at a two-decade low,[63] a consequence of policy inaction and dramatic market changes. Efficiency standards (the so-called Corporate Average Fuel Economy, or CAFE, standards) were enacted in 1975 and, after the ten-year phase-in of higher standards envisioned by the original legislation, have not seen a major increase since. With no policy incentive to deliver vehicles with improved fuel economy, automakers have focused their engineering talent on building larger, faster vehicles. The average new vehicle in 2004 has the same fuel economy as one twenty years ago, but it weighs 25 percent more, accelerates 29 percent faster, and has a 91 percent more powerful engine.[64] The rise of SUVs, minivans, and pickups (whose market share doubled over twenty years) is a driving force behind these trends, but passenger cars themselves have become significantly more powerful and heavier in their own right.[65]

Fortunately, there are ample technologies available to increase vehicular fuel economy that do not require sacrifices in performance and save consumers money. Many of the technologies are already in production today but have yet to be introduced broadly. For example, variable valve timing controls are found on the large majority of engines offered by Toyota and Honda in North America, but this fuel-saving technology is just starting to be introduced by U.S. manufacturers.[66] Some of the technologies are still emerging. Advanced direct-injection gasoline engines that deliver large efficiency gains while meeting stringent U.S. emissions standards are expected to be introduced within the next five years. And hybrid electric vehicle technology is found in several popular models today and offers large gains in efficiency.

Recent analyses by the National Research Council, MIT, and ACEEE using sophisticated computer models have demonstrated the potential for substantial fuel economy gains from implementing conventional technologies even without moving to hybrid electric designs.[67] In all cases, fuel savings discounted over the life of the vehicle more than offset the higher projected initial cost of the more fuel efficient vehicle.[68] These studies also demonstrate that hybrid vehicle technology offers even greater potential for efficiency gains by capturing a portion of the braking energy for reuse, turning off the engine whenever possible, and permitting engine efficiency gains.

For our comparison of different biofuels options, we use two different sets of vehicle efficiency assumptions. We look at current light-duty and heavy-duty vehicle fuel efficiency, and we look at fuel efficiency that we believe new vehicles will be able to achieve primarily through 2025. While additional advances are likely post-2025, we have not assumed any. Our values are based on new modeling done by UCS and are roughly consistent with findings in previous studies. By 2025, we assume that new cars, SUVs, and other light-duty vehicles will more than double their efficiency. Heavy-duty vehicles such as freight trucks will also be able to improve, but only by about 55 percent.

Table 14. New Vehicle Fuel Efficiency Assumptions

Miles per gallon	2004	2015	2025	2050
Cars	21.8	37.9	50.3	50.8
Light-duty trucks	16.5	28.8	35.8	36.1
Heavy-duty vehicles[a]	5.6	8.7	8.7	8.7

[a] HDV efficiency is reported in miles per gallon of gasoline equivalent even though these vehicles predominantly use diesel fuel.

Compared to current gasoline vehicles, dedicated ethanol vehicles can run at higher engine compression ratios. This improves the engine efficiency. Older studies of this improvement put the gains between 10 and 20 percent.[69] This would mean that while ethanol contains only about two-thirds the energy of gasoline, in a dedicated ethanol vehicle, it would be as if ethanol contained between 73 and 80 percent of the energy in gasoline. This could obviously have an impact on the amount of ethanol needed. We have not assumed that future dedicated ethanol vehicles will have an efficiency advantage over their gasoline-powered counterparts because we have not specifically modeled direct injection engines powered by ethanol. Our efficiency estimates, therefore, could be conservative with respective to dedicated ethanol vehicles.

AIR POLLUTION IMPACTS OF CURRENT AND FUTURE ETHANOL USE

As the most widely used biofuel, ethanol is a good place to start a discussion of the air impacts of biofuels use. The use of ethanol as a gasoline additive to reduce pollution is currently highly controversial. Studies by the National Research Council and EPA have concluded that the federal Clean Air Act requirement to add ethanol, or other oxygenates, is not necessary in modern vehicles.[70] However, we believe, with adequate regulatory safeguards and well-crafted policies, that the current air pollution liabilities of using low blend ethanol can be minimized to an acceptable level during a period of transition to greater use of biofuels. Ethanol used in high blends, in general, does not have significant emission problems, and indeed can help reduce emissions if properly used.

Ethanol as an additive (in low blends) has a valuable property of “leaning” out fuel rich combustion in older engines, thereby reducing emissions due to incompletely combusted fuels, carbon monoxide, and hydrocarbons (also known as volatile organic compounds or reactive organic gases). Unfortunately, increasing oxygen levels too high in an engine running fuel rich increases the emissions of another very important pollutant, nitrogen oxides (NO_x). As a consequence, the oxygen content of fuel is limited to 2 percent by weight (5.7 percent by volume). At higher levels, regulatory models predict that NO_x will significantly increase. This increase can be avoided by putting tighter controls on other fuel parameters, such as sulfur levels, but the ethanol industry cites the difficulty in adjusting these parameters as a major barrier to increased use of ethanol in air quality–constrained regions.

In theory, modern vehicles should be able to compensate for the addition of oxygenates and be able to achieve the same exhaust emissions with or without them. The primary reason is that modern vehicles have oxygen sensors, fuel injector, and computer controls to compensate for non-ideal combustion. That is, if the oxygen sensor detects too low a level of oxygen in the gases coming from the engine, the computer control can automatically compensate by reducing the amount of fuel being injected into the engine cylinder (so-called closed loop operation). Furthermore, today’s vehicles certified to California LEV II or Federal Tier 2 standards have extremely efficient catalyst systems that reduce CO, VOC, and NO_x emissions to very low levels. Hence, it is thought that the NO_x penalty from ethanol blends higher than 5.7 percent will eventually not be an issue as the fleet turns over. However, since the LEV II and Tier 2 vehicles are just entering the fleet, the problem will likely not be completely eliminated for another 15 years.

Nitrogen oxide and VOC are precursors to ground level ozone, or smog. NO_x emissions are also precursors to another major public health threat—fine particulate emissions—and they increase acid rain. Fine particulates (2.5 microns or smaller) are associated with increases in mortality rates, especially cardiopulmonary and lung cancer related mortality.[71] While ethanol should reduce emissions of coarser particulate matter (10 microns or smaller, known as PM_{10}), because of the increase in secondary formation of fine particulates potentially caused by the increase in NO_x emissions associated with ethanol blends in the existing fleet, not enough is known about ethanol's impact on overall particulate emissions. Fortunately, by eliminating any difference in NO_x emissions, the pollution control technologies in new vehicles will also eliminate concerns about fine particulates.

Exhaust emissions from vehicles running on high ethanol blends are not considered to be a problem from the perspective of criteria pollutants. However, additional testing should be performed on high blends, as well as LEV II and Tier 2 vehicles, to give air quality regulators and public health advocates the highest level of confidence that there are no air quality liabilities associated with increased use of ethanol.

In addition to tailpipe exhaust emissions, fuel can evaporate during fueling and storage and from the vehicle's fueling system, increasing ozone pollution.[72] There are two issues related to these types of evaporative emissions: 1) increased vapor pressures with low-percentage ethanol blends, and 2) permeation of ethanol through rubber and plastic components of the fuel system.

Pure ethanol has a Reid vapor pressure (RVP) four to five times lower than that of pure gasoline, meaning it will have four to five times less evaporative hydrocarbon emissions than gasoline. However, when ethanol is blended up to 40 percent with gasoline, the combined fuel actually has higher evaporative emissions than either fuel by itself. Evaporative emissions peak with a mixture that contains between 5 and 10 percent ethanol and then start to decline, reaching a level equal to pure gasoline once there is about 40 percent ethanol. Above 40 percent, ethanol's stand alone RVP starts to be predominant, and the blended fuel actually results in fewer evaporative VOC emissions than does gasoline.[73] A mixture of 85 percent ethanol and 15 percent gasoline (commonly referred to as E85) results in nearly the same four- or fivefold reduction in emissions that pure ethanol would produce.

Evaporative emissions due to increased RVP can be easily controlled, although it adds costs. Both California and federal reformulated gasoline programs require a cap on RVP during the ozone season, effectively requiring refiners to use a lower RVP base gasoline stock when blending with ethanol to compensate for the increase in RVP when the fuels are mixed. This, in turn, increases blending costs and reduces refinery output.

A more challenging problem for evaporative emissions in the near term is the so-called permeation emissions. Low ethanol blends also have higher evaporative emissions than non-ethanol blends due to permeation through the rubber, plastic, and other "soft" components of the fuel system. These emissions may be largely eliminated on new vehicles by using higher-quality hoses, tubes, and other connectors.[74] However, as with the exhaust emission problem, the permeation liability will remain a problem until all the older vehicles are eliminated. In addition, permeation is a problem for current portable cans and non-road gasoline engines (e.g., lawn mowers, motorboats, etc.).

A final category of air pollution from ethanol is the mix of toxic air pollutants emitted. The difference in these emissions is caused by what chemicals are in the fuel, though tailpipe controls can compensate for some of these. Gasoline, for example, has benzene and butadiene, some of which is emitted as air pollution. Biofuels will limit those emissions, since biofuels don't even contain those toxins. In contrast, the combustion of ethanol results in the formation of aldehydes. Because of the reactivity of aldehydes, they can generally be well controlled through tailpipe oxidation catalysts. Thus we assume that with the appropriate regulations, in vehicles optimized to burn ethanol, this problem would be controlled. Even any potential increase in aldehydes emissions would need to be weighed against the reduction in other pollutants including benzene and butadiene. Acetaladehyde and formaldehyde have between 10 and 60 times lower cancer risk factors then the gasoline related toxics (as measured by cancer unit risk estimates, or CURE).[75]

Table 15. Relative Cancer Risk Factors for Major Vehicle Exhaust Toxic Pollutants

Pollutant	**CURE $(\mu g/m^3)^{-1}$**
Acetaldehyde	2.7×10^{-6}
Benzene	2.9×10^{-5}
1,3-butadiene	1.7×10^{-4}
Formaldehyde	6.0×10^{-6}

AIR POLLUTION IMPACTS OF THE USE OF OTHER CELLULOSIC BIOFUELS

In addition to ethanol, we are examining the potential to produce Fischer Tropsch diesel and gasoline and, to a lesser extent, DME. The data on the use of Fischer Tropsch fuels are limited, especially for Fischer Tropsch gasoline. Available data suggest that when burned in a conventional engine, Fischer Tropsch diesel offers substantial tailpipe reductions in sulfur oxides and aromatics, with moderate reductions in other air pollutants.

Table 16. Emissions of Fischer Tropsch Diesel vs. Conventional[76]

Emission	Neat FTD Emissions Reduction
Hydrocarbons	22%
Carbon monoxide	28%
Nitrogen oxides	6-20%
Particulate matter	11%

ETHANOL, THE OXYGENATE REQUIREMENT, AND URBAN AIR QUALITY

As part of the Clean Air Act as amended in 1990, cities or regions with severe ozone (urban smog) or carbon monoxide pollution problems (non-attainment zones) were required to use specially blended clean gasoline. But rather than setting environmental standards for the performance of clean gasoline, the Clean Air Act mandated that gasoline in these zones be blended with oxygenates, which are chemicals that help the gasoline burn more completely and cleanly. Because of its moderate cost, methyl tertiary-butyl ether (MTBE) has been the main oxygenate of choice until recently, when it was discovered that MTBE can leak from underground storage tanks and contaminate drinking water. As a result, several states have restricted the use of MTBE, and California, New York, and Connecticut have enacted complete bans on its use. Ethanol is the primary oxygenate alternative to MTBE, and the only blending option allowed for non-attainment zones in states that have banned the use of MTBE.

NRDC opposes the oxygenate requirement and believes that its smog-fighting benefits can be achieved through new fuel blends that do not contain oxygenates and avoid the VOC and NO_x emissions caused by low-level ethanol blends. NRDC supports a renewable fuels standard as a better way to develop biofuels. A renewable fuels standard allows biofuels to be used where they are cheapest—primarily in the Midwest—rather than in urban centers with air quality problems.

It is important to note that these figures are reductions achieved for conventional vehicles run on pure Fischer Tropsch diesel without aftertreatment technology. Blends of Fischer Tropsch diesel with petroleum-derived diesel, a more likely near-term scenario, would show reduced emission benefits.[77] For future vehicles, we assume that Fischer Tropsch diesel offers no significant benefit compared to ultra-low-sulfur petroleum diesel when used in vehicles with sophisticated pollution controls. Similar to our assumptions about ethanol-powered vehicles, we assume that pollution control advances for petroleum-powered vehicles will minimize if not eliminate the current pollution advantage of non-petroleum biofuels. For these advanced vehicles biofuels are simply likely to make it easier to comply with future emissions standards, and thus potentially reduce the cost of emissions control technologies.

Table 17. Tailpipe Emissions Assumed for Advanced Vehicles

Pollutant (g/mile)	Light-Duty Hybrid Electric Vehicles[a]			
	RFG[b,d]	E85[c,d]	Diesel[e]	FT Diesel
NO_x	0.1094	0.1038	0.1206	0.1206
VOCs				
Exhaust	0.1538	0.1449	0.1538	0.1538
Evaporative	0.0705	0.0689	0.0000	0.0000
CO	6.1215	6.1763	6.1215	6.1215
PM10				
Exhaust[f]	0.0042	0.0042	0.0092	0.0092

Tire & Brake Wear	0.0208	0.0207	0.0205	0.0205

[a] Tailpipe emissions for light-duty vehicles are combined based on forecast VMT share in 2030.
[b] RFG is reformulated gasoline that meets federal fuel standards.
[c] E85 is a blend of 85 percent ethanol and 15 percent gasoline.
[d] Gasoline and E85 cars are assumed to meet federal Tier 2, Bin 2 emissions standards, and trucks are assumed to meet Tier 2, Bin 3 emissions standards.
[e] Diesel fuel is assumed to meet the 2008 highway diesel fuel standards for sulfur content of 15 ppm.
[f] Sulfur emissions are included in PM_{10} exhaust.

WATER USE AND POLLUTION IMPACTS FROM USING BIOFUELS

There are also concerns about increased water pollution from ethanol blends. In anticipation of increased ethanol use as a gasoline additive in place of MTBE, the Northeast States for Coordinated Air Use Management (NESCAUM) conducted an extensive analysis of ethanol's environmental impacts. This study assessed the negative and positive characteristics of ethanol, both as a blended and neat fuel, in order to gauge the effect increased ethanol use would have on the region.[78]

Like any fuel, and most notably gasoline and its oil precursor, neat or blended ethanol can get into waterways at any point along the way from the processing facility to the fuel tank. Leaks could occur at the facility, as the fuel is transported from the facility to bulk terminals, at blending facilities if it is used as an additive, or en route to the fueling station. Additionally, ethanol, blended at present but also neat in the future, can escape from aboveground or underground storage tanks as well as during fueling.

Ethanol, however, has the advantage of being 100 percent water soluble and readily biodegradable, compared to MTBE's 4 percent solubility and poor biodegradability, both of which have led to the latter's phase-out nationally. Therefore, it is a significantly smaller threat to groundwater. However, these beneficial characteristics of ethanol can amplify gasoline's harmful properties when the two are blended together. Because of its biodegradability, ethanol's rapid breakdown by microbes depletes available oxygen in soil and water, thereby slowing the breakdown of gasoline. As a result, harmful chemicals in gasoline, such as benzene, toluene, ethylbenzene, and xzylene (collectively BTEX), persist longer than otherwise would be the case. When ethanol is blended with gasoline, benzene, specifically, can persist 10 to 150 percent longer than it would in a pure gasoline spill.[79]

Similarly, ethanol can act as a carrier, extending the distance that gasoline, and its toxic BTEX compounds, can travel by perhaps as much as 2.5 times, according to modeling and laboratory studies. However, this seems to be a significant factor only when ethanol makes up 20 percent more of the fuel mixture. Blending aside, if spilled, ethanol can also remobilize residual gasoline in contaminated soils, further exacerbating the effects of the gasoline's initial spill. This is most likely to be a problem at gasoline terminals where spills have occurred at up to 85 percent of facilities.[80]

For water pollution the conclusion is similar to VOC emissions: ethanol presents a challenge in the transition period. Once we are using only high-blend mixtures of ethanol, ethanol's lower toxicity and greater biodegradability should make it much less of a water pollution threat.

To manage these impacts, we need to plan our transition accordingly. Among other steps, we should not force the use of low ethanol blends into urban areas that already have high background levels of these pollutants. We also need to require that new vehicles be optimized to burn biofuels as soon as possible. While there are currently minor additional costs to vehicles that can burn both petroleum fuels and biofuels, these costs would become trivial if all vehicles were required to have this capability. On the water pollution side, the federal government needs to establish fuel handling regulations that recognize the potential threat from low ethanol blends.

CHAPTER 6

ASSESSING DIFFERENT BIOFUEL OPTIONS

We have looked at growing switchgrass, converting it into biofuels, and using these fuels in our cars and trucks. Now we have to put it all together. Our analysis of eight different packages of processing technologies and products shows that biofuels can be cost competitive with gasoline and diesel, and that there are packages of technologies that can provide significant reductions in our oil use and our greenhouse gas emissions simultaneously. Recall that the eight different technology-product combinations that we have analyzed are:

1. Ethanol from CBP and power coproduction from CBP residues via Rankine cycle
2. Ethanol from CBP and power coproduction from CBP residues via gasification
3. Ethanol from CBP and Fischer Tropsch fuels coproduction from CBP residues via gasification
4. Ethanol from CBP and power coproduction via Rankine cycle and animal protein coproduction
5. Fischer Tropsch fuels and power coproduction via gasification
6. Dimethyl ether and power coproduction via gasification
7. Power from Rankine cycle
8. Power from gasification

Our analysis of these combinations involves a two-step process. In the first step we have done detailed engineering designs for these eight different types of production facilities and validated the design using an engineering design model known as ASPEN Plus, which tracks the flow of materials and the thermodynamics of the design.[81] With the validated design, we know all of the components needed, the amounts of different inputs, and the outputs including key air and water pollutants. Based on this, we can move on to the next step, the economics. This involves figuring out how much it would cost to build a plant matching our design. For this we use an equipment costing database and economic model that calculates the project's finances and the necessary cost of the final product. For the oil displacement and greenhouse gas reductions, we use Argon National Laboratories GREET model, which allows us to assess the life cycle impacts of fuels produced from facilities matching our designs.

While we look at the economic competitiveness of different biofuels technologies on a simple dollar per gallon basis, we consider oil displacement and greenhouse gas reductions in terms of the impact per ton of biomass used. This allows us to address the question of how we can get the most out of our biomass resources in terms of these two criteria.

BIOFUELS CAN COMPETE WITH GASOLINE AND DIESEL PRICES

Based on our analysis, advanced biofuels facilities should be able to produce cellulosic ethanol at a cost between \$0.39 and \$0.69 per gallon at the plant gate, depending on the scale of the facility and the other products that the facility coproduces. These costs are competitive with recent, current, and expected future wholesale prices of gasoline. The most cost-competitive configurations are those that produce ethanol, electricity, and animal feed protein. The configurations that also produce Fischer Tropsch diesel can sell this fuel at a competitive price, but these facilities have to be larger and gasoline and diesel prices have to lean toward the higher end of what is expected for the facilities to make economic sense.

There are two important lessons that our economic analysis makes clear: size matters and coproducts matter. However, while bigger is better (to a point) in terms of economics, more coproducts is not always better. Size matters because there are economies of scale. It is common today to think of biomass facilities as relatively modest affairs. Typically analysts talk about cellulosic biofuels facilities that use a few hundred to 1,000 tons of biomass per day. In our analysis we have focused on facilities that use 5,000 to 20,000 tons per day. Achieving these scales dramatically improves the economics of biofuels production.

These sizes are large only in comparison to current thinking about cellulosic biofuel plants. In terms of the tonnage of material fed to a conversion facility, a 5,000 dry ton per day scale is comparable to the average corn ethanol wet mill (200,000 bushels per day, or 5,600 tons per day). The largest wet mill—ADM's Decatur, Illinois plant—processes 555,000 bushels a day, about 15,500 dry tons per day.[82] The largest oil refinery processes more than 550,000 barrels per day, or 77,300 tons per day; the average refinery runs about 150,000 barrels per day, or 21,000 tons per day.[83] While the low density of switchgrass would present logistical hurdles at these scales, based on our discussions with experts in this field, we do not believe these challenges would be insurmountable. Given these examples, it seems that cellulosic biofuels plants larger than 5,000 to 20,000 dry tons per day would indeed be feasible.

Scale is especially important for the economics of biofuels production. Figure 6 illustrates this. This figure shows our cost estimate for ethanol coproduced with electricity using steam Rankine technology. Costs are much higher at the smaller end of the scale range. At about 5,000 tons per day of switchgrass input to a facility, the cost per unit of ethanol begins to "flatten," though cost reductions continue with increasing scale. These calculations assume a fixed price for feedstock biomass. Presumably, larger plant sizes will pay more on average for biomass than small plants, since transportation distances would be higher. However, prior analyses have shown that increased biomass costs that accompany increased scale are more than compensated for by decreased unit capital costs that accompany increasing plant size, giving the net result of lower product cost for very large plant sizes.[84]

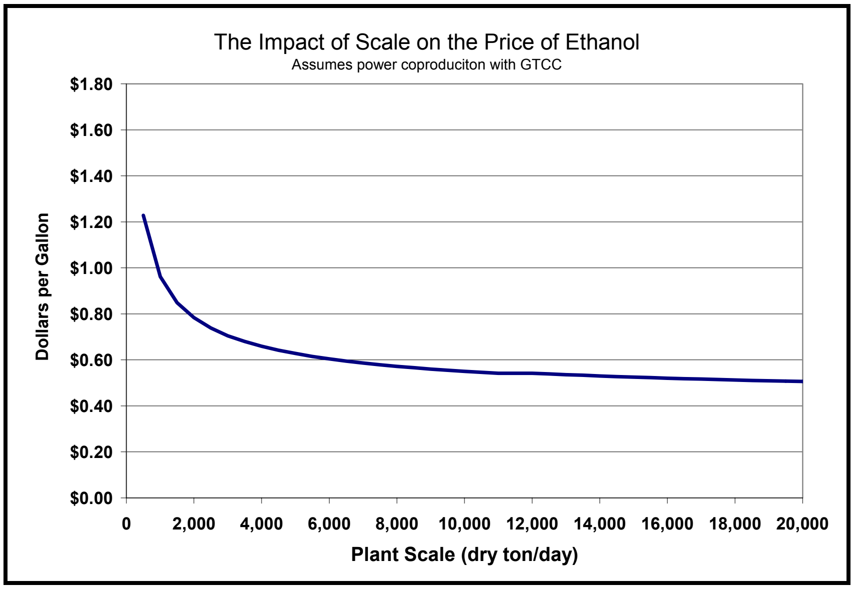


Figure 6. Size Matters for Biofuels Costs

Coproduction of a biofuel with other products also can help the economics, as long as the additional cost of processing is not more than the increased revenue. For example, the coproduction of ethanol, power, and protein is the most cost-effective option we have identified. Assuming that switchgrass protein can fetch a price equal to the average price of soymeal protein since 1980 ($0.20 per pound), this configuration can produce ethanol at just $0.39 per gallon.[85] This is $0.59 per gallon of gasoline and substantially lower than both the average wholesale price over the last four years and the Department of Energy's base-case forecast for 2025.

In contrast, the coproduction of ethanol, Fischer Tropsch fuels, and power produces fuels that are more expensive. While they are below average recent prices, they are above forecasted prices in 2025 and the ethanol is more expensive than that coproduced with animal feed protein. However, this configuration displaces the greatest amount of oil of all those that we have analyzed. In future analysis we will combine these options, and we expect to be able to lower the cost of biofuels while maintaining most of the oil displacement benefits.

Table 18 presents our cost estimates for producing biofuels and power from our eight different configurations. In all cases where at least one fuel is being produced, we have assumed that the electricity co-product will sell for $0.04 cents per kWh. If electricity prices are higher, then those configurations that produce more electricity will be able to lower the price of biofuels even more than the others, and the converse is true as well. Those cases with the largest amount of electricity co-product, namely the Fischer Tropsch fuels and power and DME and power cases, will be most sensitive to electricity price. Configurations 7 and 8 only produce power, so the price of electricity reported for these configurations is the price that the technology can achieve. For configuration 4, which produces ethanol, power, and protein, we have assumed that protein will have a value of $0.20 per pound.

Table 18. Estimated Cost of Biofuels and Power from Advanced Technologies[86]

Scenario		5,000 Tons per Day				20,000 Tons per Day			
		$/gal ethanol	$/gal gasoline equiv	$/gal diesel equiv	$/kWh	$/gal ethanol	$/gal gasoline equiv	$/gal diesel equiv	$/kWh
1	EtOH/Rankine	$0.60	$0.91		$0.040	$0.52	$0.77		$0.040
2	EtOH/GTCC	$0.63	$0.95		$0.040	$0.51	$0.77		$0.040
3	EtOH/FT/GTCC	$0.72	$1.09	$1.02	$0.040	$0.60	$0.91	$0.86	$0.040
4	EtOH/Protein/Rankine	$0.49	$0.74		$0.040	$0.39	$0.59		$0.040
5	FT/GTCC			$1.56	$0.040			$1.09	$0.040
6	DME/GTCC			$1.58	$0.040			$0.95	$0.040
7	Rankine				$0.049				$0.042
8	GTCC				$0.046				$0.039

Gasoline and diesel prices are notoriously volatile of late, and there is a long history of forecasts of renewable technology cost competitiveness that have proven wrong when the price of the fossil fuel alternative has gone down. For the sake for comparison, we present a wide range of wholesale spot prices for gasoline and diesel. The first set is based on historical daily prices between the beginning of 2000 and early November 2004. Table 19 shows the maximum, average, and minimum prices during that period. We also present estimates of spot prices in 2025. These are based on Department of Energy forecasted wholesale crude oil prices and the historical relationship between crude oil prices and gasoline and diesel prices. There may be technology innovations in oil exploration, drilling, and refining. Even absent innovation, we should keep in mind that oil prices are in large part currently controlled by OPEC, an oligopoly.

Table 19. Recent and Forecasted Wholesale Gasoline and Diesel Prices

2000–2004	**High**	**Average**	**Low**
Gasoline	$1.50	$0.91	$0.44
Diesel	$1.62	$0.85	$0.46
Forecast for 2025	**High**	**Base**	**Low**
Gasoline	$1.03	$0.79	$0.48
Diesel	$0.98	$0.74	$0.44

THE LIFE CYCLE BENEFITS OF BIOFUELS

Overall our life cycle assessment of our eight configurations offers three lessons: 1) to maximize oil displacement, we should use biomass to make biofuels; 2) greenhouse gas reductions depend heavily on how one assumes the electric sector will change over time; and 3) there are packages that provide significant benefits regarding both oil displacement and greenhouse gas reductions.

Given that we use very little oil to produce electricity and use almost exclusively oil to produce motor vehicle fuels, it follows that using biomass to produce biofuels displaces much more oil than using it to make power. Accordingly, the configuration that produces the most total biofuels also reduces oil demand the most. Among the options that we have analyzed to date, this configuration is the one that coproduces ethanol, Fischer Tropsch fuels, and power.

Interestingly, the configuration that coproduces ethanol, power, and animal feed protein displaces the next largest amount of oil, though it is followed closely by those configurations that just produce ethanol and power. This is because protein production through soybeans actually requires a fair amount of oil, primarily during cultivation.

Beyond the two power-only configurations, the two configurations that coproduce diesel alternatives (Fischer Tropsch diesel and DME) and power provide the least oil displacement, simply because they produce the least amount of fuels. Table 20 summarizes the barrels of oil displaced per ton of biomass used in each of the eight configurations we have modeled.

Table 20. Oil Displacement per Ton of Biomass[87]

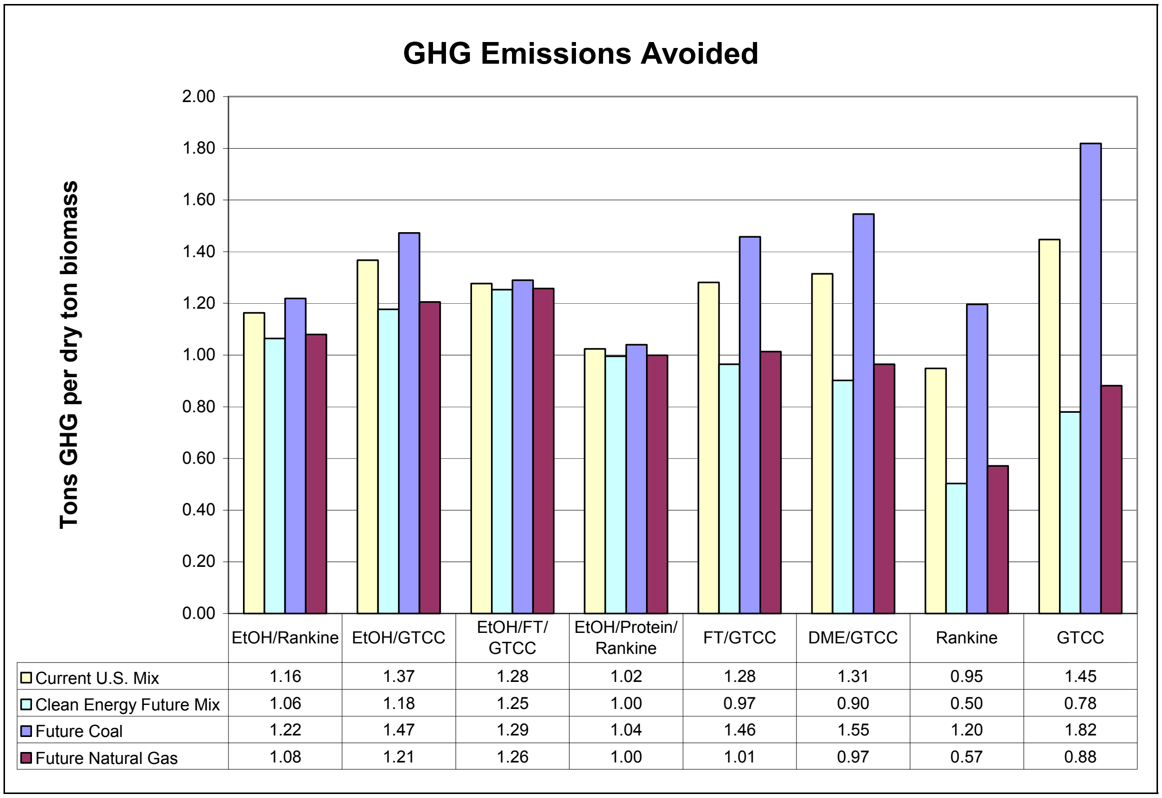
Configuration	Barrels of Oil per Dry Ton of Biomass
1. EtOH/Rankine	1.57
2. EtOH/GTCC	1.59
3. EtOH/FT/GTCC	2.04
4. EtOH/Protein/Rankine	1.64
5. FT/GTCC	1.00
6. DME/GTCC	0.71
7. Rankine	-0.02
8. GTCC	0.02

These same two configurations that produce alternatives to diesel are good examples of some of the complexities of assessing greenhouse gas reductions as well as the balancing that can go on between oil displacement and greenhouse gas reductions. Given the current mix of fuels used to generate electricity in the United States using a ton of biomass to generate electricity provides a moderately larger reduction in greenhouse gases than any of our fuel producing options. This situation will change over time, though, especially if we make a concerted effort to reduce overall greenhouse gas emissions. We use as a benchmark of potential improvements to the greenhouse gas intensity of the electricity mix a study called "Scenarios for a Clean Energy Future," done jointly by five of the Department of Energy funded national energy laboratories.[88] This study forecasted a much greater reliance on renewables and natural gas. If we achieved this mix, then producing fuels would provide a greater greenhouse reduction.

An alternative approach to assuming a future mix is to assume that power generation from coal—the most carbon intensive fossil fuel—and from natural gas—the least carbon intensive—more or less bound the range of potential performance from the power sector. Of course even these technologies will change over time, so we use their expected future performance to provide our benchmarks.

Based on displacing our current power mix or coal, the two configurations that produce alternatives to diesel also produce some of the largest greenhouse gas reductions among our eight configurations, in large part because they coproduce so much power. Thus, in the near term if we prioritized greenhouse gas reductions over oil displacement, but still wanted to achieve some of both, then these configurations would be good starting points. However, if only natural power plants were displaced, these configurations would provide less greenhouse gas reductions, and if we achieved a future heavy in renewables, then these configurations would actually perform the worst among our configurations.

The two best-performing biofuels configurations are coproducing ethanol and electricity via gasification and coproducing ethanol, Fischer Tropsch fuels, and electricity. In particular these configurations fare well under all the potential fuel mixes, making them robust greenhouse gas reduction strategies.



	EtOH/Rankine	EtOH/GTCC	EtOH/FT/ GTCC	EtOH/Protein/ Rankine	FT/GTCC	DME/GTCC	Rankine	GTCC
☐ Current U.S. Mix	1.16	1.37	1.28	1.02	1.28	1.31	0.95	1.45
☐ Clean Energy Future Mix	1.06	1.18	1.25	1.00	0.97	0.90	0.50	0.78
☐ Future Coal	1.22	1.47	1.29	1.04	1.46	1.55	1.20	1.82
■ Future Natural Gas	1.08	1.21	1.26	1.00	1.01	0.97	0.57	0.88

Figure 7. Greenhouse Gas Emissions Reductions

If we are serious about reducing our greenhouse gas emissions in the power sector and the transportation sector, it will become increasingly important to focus on producing biofuels. In the near term, there is a mild advantage to using biomass for power, and this must be weighed against the energy security benefits of displacing oil and the economics.

For the rest of the analysis in this report—including the land-use analysis in Chapter 3 and in the plan for biofuels in the next chapter—we actually focus on a configuration that we have not yet finished analyzing. We assume a configuration that coproduces ethanol, Fischer Tropsch fuels, electricity, and animal feed protein. This package promises the cost and land-use benefits that come from coproducing animal feed and the oil displacement and greenhouse gas benefits of coproducing ethanol, Fischer Tropsch fuels, and electricity.

CHAPTER 7

A PLAN FOR USING BIOFUELS TO SLASH OUR OIL DEPENDENCE

The main reason that cellulosic biofuels technology is not further developed today is the lack of a sustained commitment to overcome the technical challenges and to reduce our dependency on oil. These are the same reasons that no type of biofuel provides more than a few percent of our transportation energy needs. So far we have argued that biofuels derived from cellulosic biomass such as switchgrass have tremendous technical potential and that solutions to the technical challenges are readily foreseeable. We have argued that biofuel can provide great environmental benefits and that the challenges that arise during the transition to biofuels can be overcome if we address them head on. And we have seen how biofuels could increase farm income and compete with gasoline and diesel.

Farmers are necessarily focused on the next few growing seasons and policy makers on the next election cycle. They will both rightly ask, how soon could cellulosic biofuels become a big player, and what is it going to take to get us there? We address these questions next.

BIOFUELS CAN MAKE A LARGE CONTRIBUTION SOON

Assuming an aggressive national research, development, demonstration, and deployment (RDD&D) program starting in the next few years, we believe that by 2015 the United States could have 1 billion gallons of cellulosic biofuels production capacity and be ready to put in place technology that can be cost competitive with gasoline and diesel. By itself, 1 billion gallons represents less than half of 1 percent of our total transportation oil use, but at the end of this initial stage of RDD&D, biofuels would be poised for head-to-head competition with gasoline and diesel and would have the potential for rapid growth.

In the next section, we lay out a "pedal-to-the-metal" growth scenario for biofuels. We find that we could produce about 180 billion gallons of biofuels by 2050. Understanding this potential for growth helps put a near-term aggressive policy push in perspective. The cost and effort may seem like a lot relative to the benefits of 1 billion gallons, but it is clearly modest relative to this potential.

We are not claiming that initial economic competitiveness is all that is needed for cellulosic biofuels to achieve all of their potential. In fact, given the inertia created by the amount of oil-related assets and the end-user lock-in that gasoline and diesel enjoy, government policies may be needed (and be cost effective) to continue to drive adoption of cellulosic biofuels well beyond the opening of the first commercially competitive cellulosic biofuels production facility.

Policies such as a renewable fuels standard could dovetail very neatly with the RDD&D policies discussed below. Just as environmental regulations will be essential to guide the development of biofuels in a sustainable way, policies to continue to drive the market for biofuels will be essential to avoid the hourglass effect in the market—where the market shrinks in anticipation of a new technology. Again the tremendous potential identified in the next section puts these relatively modest efforts into context.

OIL SAVINGS FROM BIOFUELS IN 2025, 2030, AND 2050

Commercial investment in cellulosic biofuels may start in earnest with any of the biofuels we have discussed here. However, cellulosic ethanol has the advantage that it can start competing in higher-value markets as an oxygenate and octane enhancer. If the United States adopts a renewable fuel standard sized primarily for the corn ethanol industry and does not update it, cellulosic biofuel could start competing with corn ethanol for a mandated biofuels requirement. However, these markets are limited to just a few percent of our total gasoline demand and would force corn ethanol and cellulosic biofuels to compete, limiting the benefits of both. As we have already suggested, a better alternative would be a mandate that increases as cellulosic biofuels become available.

Under any of these scenarios, once the technology reaches commercial scale and cost competitiveness, the initial stage of development for the industry is likely to be exponential. Eventually the industry is likely to hit limits to its growth ranging from the amount of investor capital available to the number of construction companies able to build plants. The limits will shift growth from exponential to linear, where the same amount is added every year. These limits can certainly be impacted by policy; thus both the initial growth rate and the eventual maximum number of gallons per year that can be added are functions of our national commitment.

We can draw examples of achievable exponential and linear growth rates from other industries. The corn ethanol industry is a useful example of a related industry that has shown extremely high growth rates due almost entirely to government policies. The corn ethanol industry grew 30 percent in 2003 and has shown growth of up to 60 percent in one year.[89] Its ability to grow at this rate suggests two things. First, strong government support can encourage growth of an industry even against the tide of the economy. Second, the ability to increase capacity is available for biomass processing. Increases of this scale imply that, for fermentation processes, we have the skills required to design and build plants, obtain feedstock, and operate the plants successfully.

We can also look at what the petroleum refining industry has done in the past to get an idea of future potential. As Figure 8 shows, gasoline production capacity increased steadily through 1980 and actual production has been even more consistent over the last 53 years (1949 to 2002). The average increase in the amount of oil that could be processed was 6 billion gallons per year and the largest increase was 18 billion gallons. In terms of actual gasoline production, it increased on average by 2 billion gallons per year with a maximum of 6 billion gallons.[90] Per capita GDP today is 1.8 times what it was in

1972, when gasoline production increased by 6 billion gallons. It is not unreasonable, therefore, to think that in an aggressive scenario, this much productivity could be added to the cellulosic biofuels industry each year.

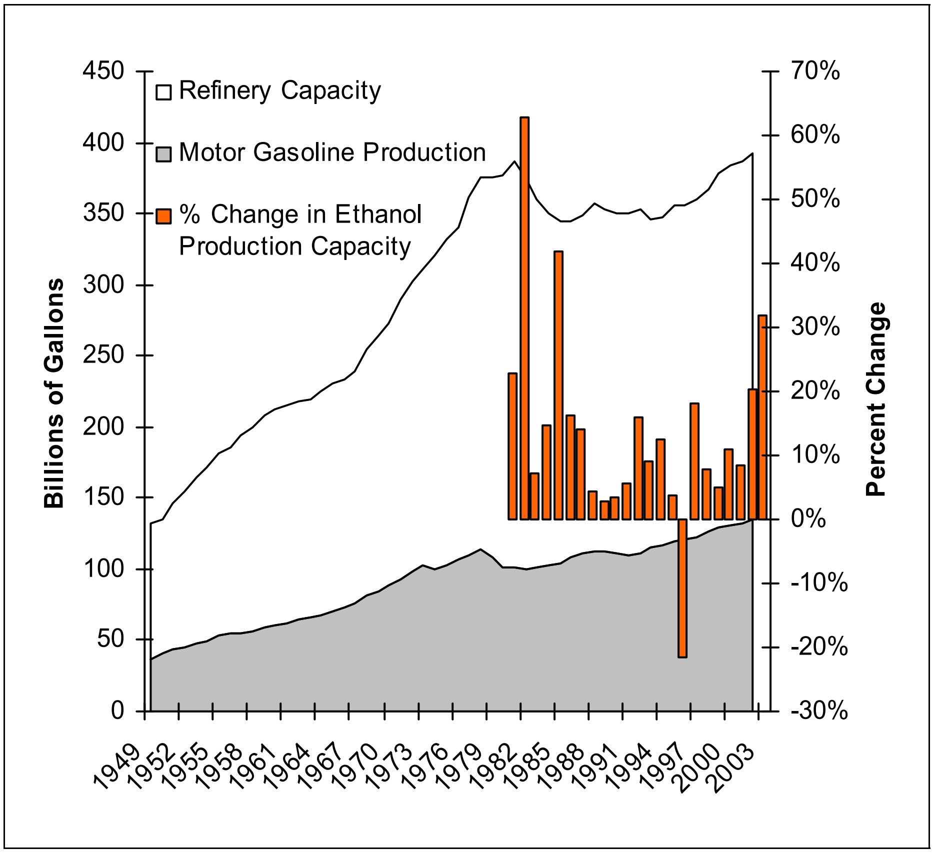


Figure 8. Gasoline Refining Capacity and Production 1949–2002

In addition to building new production facilities, if the biofuels industry is to grow at an aggressive rate, it must be able to obtain a rapidly increasing supply of feedstock. Between 1986 and 1990, the Conservation Resource Program enrolled an average of 8.5 million acres per year in response to an average rental payment of $48 per acre per year.[91] This is well above the roughly 6 million acres that would be needed to support a maximum increase of 6 billion gallons per year. While maintaining this rate of crop conversion through 2050 would be a significant challenge, at $40 per ton and yields of between 5 and 12.5 tons per acre, farmers would receive between $200 and $500 per acre for growing switchgrass. Thus it appears that crop conversion rates would not act as a limiting factor.

However, there is a limit on the amount of land that can be sustainably devoted to energy crop production. Earlier, we walked through an example showing that we could meet nearly all of our expected gasoline demand in 2050 on land currently under cultivation while continuing to meet our other agricultural needs. In this example, we showed how we could meet this expected demand with the amount of biomass that could be grown on 114 million acres, and we then identified ways to integrate cellulosic biomass demand into current agricultural practices so that we would need only 6 million additional acres or 74 million tons of biomass under our most aggressive scenario. While we believe that farms will be innovative enough to find ways to produce this much additional biomass, for now we will limit our pedal-to-the-metal scenario to the amount of fuel that could be produced on 108 million acres.

Based on these examples, for our pedal-to-the-metal scenario, we use a 30 percent initial growth rate that is capped at 6 billion gallons per year. With these parameters and assuming the industry starts its growth in 2015 with a base of 1 billion gallons, the production of biofuels grows at the exponential 30 percent rate until 2027, when the annual growth cap is hit. Our land restriction does not come into effect until 2047, a further indicator that land is not as big a hurdle as some may have thought. As a result, in 2025, the production is 13.8 billion gallons of cellulosic ethanol per year. By 2030, production reaches 41.3 billion gallons per year, and from 2047 through 2050, it is 139.7 billion per year. With the coproduction of Fischer Tropsch diesel and gasoline, these levels of production give us a total of 102 billion gallons of gasoline alternative and 16 billion gallons of diesel alternative in 2050. This is the equivalent of 7.9 million barrels of oil per day in 2050—nearly half of all the oil that we currently use for transportation.

Obviously this is not an exhaustive analysis, but it allows us to paint a picture of what an aggressive effort to commercialize and adopt cellulosic biofuels could achieve. The same project that has developed the analysis described in this report is also developing a transition model that looks at the development of a cellulosic biofuels market in much greater detail. The results of this modeling effort will be reported on elsewhere.

To understand how big a contribution this much cellulosic biofuels would make, we need to understand how much gasoline and diesel we will be using over this period of time. We currently use about 137 billion gallons of gasoline and 46 billion gallons of diesel per year to fuel our transportation sector. We also use other petroleum products equivalent to an additional 41 billion gallons of gasoline in our transportation sector. All told, we use 14.8 million barrels of oil per day for transportation purposes. By 2025 under a business-as-usual case, this number will grow to 22.9 million barrels per day and by 2050 it will top 31.7 million barrels per day.[92] Against this background, even our 7.9 million barrels a day worth of biofuels seems small. It would make up a little less than half of the expected growth. This is certainly not trivial, but it would still leave us vulnerable to the security, environmental, and economic risks posed by our addiction to oil.

Even if we could build more cellulosic biofuels plants and build them faster than we have estimated in our pedal-to-the-metal scenario, trying to meet all of this business-as-usual demand would impose unacceptable environmental costs in land if nothing else. This is true for all alternatives to oil including hydrogen and electric vehicles.

More efficient use of oil has been a goal of many for decades, mostly for the direct benefits in terms of the reduced security, environmental, and economic risks we discussed earlier. To this list of benefits we should add enabling alternatives to oil. This is why taking a package approach to reducing oil dependency is so crucial. Fortunately the potential oil savings from efficiency and smart growth are tremendous, and there are policies ready to implement that could capture these savings.

OIL SAVINGS FROM IMPROVED FUEL EFFICIENCY

The potential to improve the fuel efficiency of our cars and trucks is enormous. Our modeling suggests that fuel efficiency alone could reduce our transportation related oil demand by 35 percent. We use new modeling done by UCS that assumes various packages of efficiency technologies are adopted over time. The packages modeled are by no means the only opportunities for improving fuel economy, but represent a likely range of potential improvements.[93] The model tracks the dynamics of the fleet, including sales, aging, and retirements, and the response of drivers to different economic signals such as the price of fuel and the cost of driving. This allows for a very detailed understanding of how the fleet will change over time and how fuel efficiency improvements will be translated into actual energy savings.

For light-duty vehicles, cars, light-duty trucks such as SUVs, and commercial light-duty trucks are modeled in detail. The fuel efficiency improvements for these vehicles are based on a detailed analysis of compact cars, midsize cars, minivans, mid-size SUVs, and full-size pickups.[94] The costs of efficiency improvements are projected separately based on engineering estimates and models assuming mass production volumes.[95] With appropriate lead time, costs to manufacturers and consumers can be minimized if technology changes can be incorporated into the existing redesign schedule of vehicle platforms. The time between major platform redesigns varies by manufacturer and model, but they typically occur every four to six years.[96] Combined with several years of engineering and design lead time, it is reasonable to expect that the conventional technology improvements embodied by the advanced case would be achievable in less than ten years so that the average new car could exceed 37 miles per gallon (MPG) by 2015. We assume a similar length of time is required to shift all vehicles to hybrid designs, even though such vehicles are sold in limited numbers today, so that by 2025 all new cars exceed 50 MPG. As new vehicles are bought and old vehicles retired, the fleetwide average increases. Table 21 presents light-duty fleetwide average fuel efficiency that results over time in our modeling and, for comparison purposes, baseline business-as-usual fleetwide averages.

In developing long-run scenarios of new light-duty vehicle fuel economy, we make three additional adjustments to our estimates of fleetwide fuel economy potential: (a) We assume that historic trends in vehicle performance will continue through 2015, slightly eroding potential fuel economy increases. (b) We assume that the heaviest light trucks (those over 6,000 pounds gross vehicle weight rating) will not employ the most aggressive hybrid designs because they are more likely to have extreme towing needs. (c) We assume a baseline market share of hybrid vehicles growing from today’s levels.[97] The resulting scenario yields a fleetwide new light-duty vehicle fuel economy of 32.7 MPG by 2015 and 41.9 MPG by 2025 (and roughly flat thereafter).

For medium- and heavy-duty vehicles, there are fewer data available on potential efficiency improvements. For these trucks, the UCS modeling relies on estimates of potential fuel efficiency improvements done by the American Council for an Energy Efficient Economy.[98] That study explored the potential for fuel savings in the heavy, medium, and commercial light truck classes. ACEEE considered hybridization as well as assorted conventional technology improvements, mainly focused on aerodynamics, thermal management in engines, and auxiliaries. Recognizing that such technologies are not suitable for all trucking applications, the study also identified the fraction of vehicle miles traveled to which the technology could be applied in each class. Our resulting analysis assumes that new medium-duty vehicles could improve their fuel efficiency by 25 percent by 2015 and that new heavy-duty vehicles could improve theirs by more than 50 percent. Table 21 also presents the medium- and heavy-duty fleetwide average fuel efficiency that results over time in our modeling.

Table 21. On-Road Fleetwide Average Fuel Economy

Miles Per Gallon[a]	2004	2015	2025	2050
Baseline				
LDVs	19.6	19.6	19.8	19.8
HDVs	5.6	5.7	6	6.2
MDVs	8.5	8.6	8.5	8.5
High Efficiency				
LDVs	19.6	24.6	34.1	41.7
HDVs	5.6	6.9	8.1	8.7
MDVs	8.5	9.4	10.3	10.7

[a] All values are presented in miles per gallon of gasoline equivalent.

Based on vehicle efficiency, the number of vehicles of different types and the number of miles each vehicle is driven, the UCS modeling allows us to calculate the total amount of energy used. For a baseline we have used the Department of Energy’s Annual Energy Outlook from 2003. In comparison to this baseline, we believe that fuel efficiency improvements could save more than 140 billion gallons of gasoline and more than 33 billion gallons of diesel in 2050. This is the equivalent of 9.2 and 2.2 million barrels of oil per day or 35 percent of all of the oil that would otherwise be used in the transportation sector in 2050.

By far the simplest approach would be to simply increase the CAFE standards. Additional strategies include manufacturer and consumer incentives, or other pricing policies such as gas taxes. Whatever path taken, it is clear that the technology exists to dramatically increase the efficiency of our vehicles if we decide to get serious about reducing our dependency on oil. We addressed the technical potential for increased vehicle efficiency earlier. Here we look at the potential savings form smart growth as well.

OIL SAVINGS FROM SMART GROWTH

In addition to measures that reduce the amount of energy used for every mile traveled by the U.S. vehicle fleet, an aggressive policy to reduce oil dependency should also include measures that will reduce the overall number of vehicle miles traveled (VMT). Such policies, commonly referred to as “smart growth,” change our built environment over time. Smart-growth development includes a greater mix of housing and development types as well as more transportation options including transit and walking.

Many recent studies confirm that changes in the built environment affect travel demand. The conclusion of these studies is that smart-growth characteristics—such as increases in density, mixing land uses, design changes, and wider regional accessibility of different land uses—can have large cumulative effects on VMT.[99] Recent studies by the EPA have found that "infill" development and redevelopment of older suburbs could reduce VMT per capita by about 15 to 60 percent (depending on the metropolitan area studied) compared to "greenfield " sprawl.[100] And by examining development patterns in the nine-county San Francisco Bay Area and the five counties in and around Los Angeles, NRDC researchers have found remarkable similarities between ways that density and the urban form influence regional car ownership and driving levels.[101] In areas with smart-growth characteristics such as viable transportation alternatives, families find it less necessary to drive.

Examples abound that prove smart growth saves oil. By carefully coordinating transit planning and development, Portland, Oregon, absorbed a 26 percent growth in population from the mid-1980s to the mid 1990s while experiencing a growth of only 2 percent in traffic and reducing average commute time, energy consumption per capita, and air-quality violations.[102] And a recent study of the American Northwest found a correlation between reduced gasoline consumption and smart-growth policies.[103] In 2002, weekly gasoline use per capita was 9.7 gallons in Idaho, which has virtually no growth controls, while it was more than 45 percent lower in neighboring British Columbia with its policies that spur more compact development and walkable, transit-friendly communities.[104] Furthermore, each consumer in stateside neighbors that require the adoption of urban growth boundaries statewide—Oregon and Washington—consumed more than one gallon a day less than did residents in sprawling Idaho.[105]

To model VMT reduction, we assumed that VMT policies would change only light-duty vehicle miles traveled. For these vehicles, we adapted numbers from the Car Talk project.[106] That study concluded that after 30 years of transit, bicycle, and pedestrian-oriented initiatives but no change in fuel price, vehicle miles traveled were reduced by 18.6 percent.[107] To model the VMT reduction through 2050, the decrease from baseline VMT was ramped up linearly from zero in 2005 to 18.6 percent in 2035, and continued at the same rate to reach a final value of 27.9 percent in 2050. The reduction in the cost of driving from more efficient vehicles "takes back" about two-thirds of the reduced VMT. Thus in the baseline scenario light-duty vehicle VMT reaches 6.1 trillion miles, in the Car Talk scenario VMT reaches only 4.5 trillion, and in the combined efficiency and smart growth scenario VMT reaches 5.4 trillion.

Not only do more efficient vehicles take back some of the driving reductions, but because a more efficient car uses less gasoline to drive each mile, assuming more efficient vehicles makes the benefits of smart growth look smaller. If everyone were driving gas-guzzlers, then each mile not driven would save more gasoline. As a result, we estimate that, with fuel efficiency measures in place, smart growth policies could save 2.6 billion gallons of gasoline and about an equal number of gallons of diesel. This is the equivalent of nearly 3 million barrels of oil per day or about 9 percent of the total oil that would be used absent both smart growth and fuel efficiency.

There are reasons to be cautiously optimistic that policy makers already realize the importance of smart growth in reducing oil dependence. In 2003, the second reauthorization cycle began since the landmark Intermodal Surface Transportation Efficiency Act (ISTEA) was signed into law in 1991. In that statute, federal funds were better targeted to maintenance of the current system, flexibility was "built in" so that alternative forms of transportation such as transit and biking were given more resources, funding was dedicated to environmentally beneficial projects, and clean air was assured through a close connection with the Clean Air Act Amendments of 1990. These and other beneficial programs were continued under the 1998 reauthorization of transportation spending, the "Transportation Equity Act for the 21st Century," which increased spending by 40 percent over ISTEA. In a renewal bill, Congress may once again increase future commitments well above the current level.

Several states, most notably Oregon, have adopted smart-growth policies that reduce sprawl and fuel use. States are largely responsible for land-use planning, and as such have an important role. As the American Planning Association has stated, "[e]very political barometer—polls, legislation, executive orders, budget proposals and ballot initiatives—indicates planning reform and smart growth are major state issues."[108] However, one recent study found that as of 1999 only 11 states had adopted comprehensive statewide growth management statutes.[109] Other states must apply the lessons from Oregon by adopting similarly effective smart-growth policies.

COMBINED OIL SAVINGS FROM BIOFUELS, FUEL EFFICIENCY, AND SMART GROWTH

Under business as usual, we could easily be using 31.7 million barrels of oil per day in 2050 to fuel our light-duty vehicles. If we improve our vehicle fuel efficiency as discussed, our demand would drop to 20.3 million barrels per day in 2050. Layer in smart growth policies reducing the number of miles that light-duty vehicles drive and demand falls to about 17.6 million barrels per day. Now the 7.9 million barrels worth of oil that we displace with cellulosic ethanol under our aggressive scenario leaves us demanding with just 10.4 million barrels of oil per day for our entire transportation sector. That's a 30 percent reduction in our current transportation oil demand. It's hard to imagine how much this would reduce our security, environmental, and economic risk.

Moreover, this would virtually eliminate our demand for gasoline. Under business as usual, we would consume nearly 290 billion gallons of gasoline in the transportation sector in 2050. Between cellulosic ethanol and Fischer Tropsch gasoline and efficiency and smart growth measures that would reduce gasoline demand, we could reduce this to just 6 billion gallons.

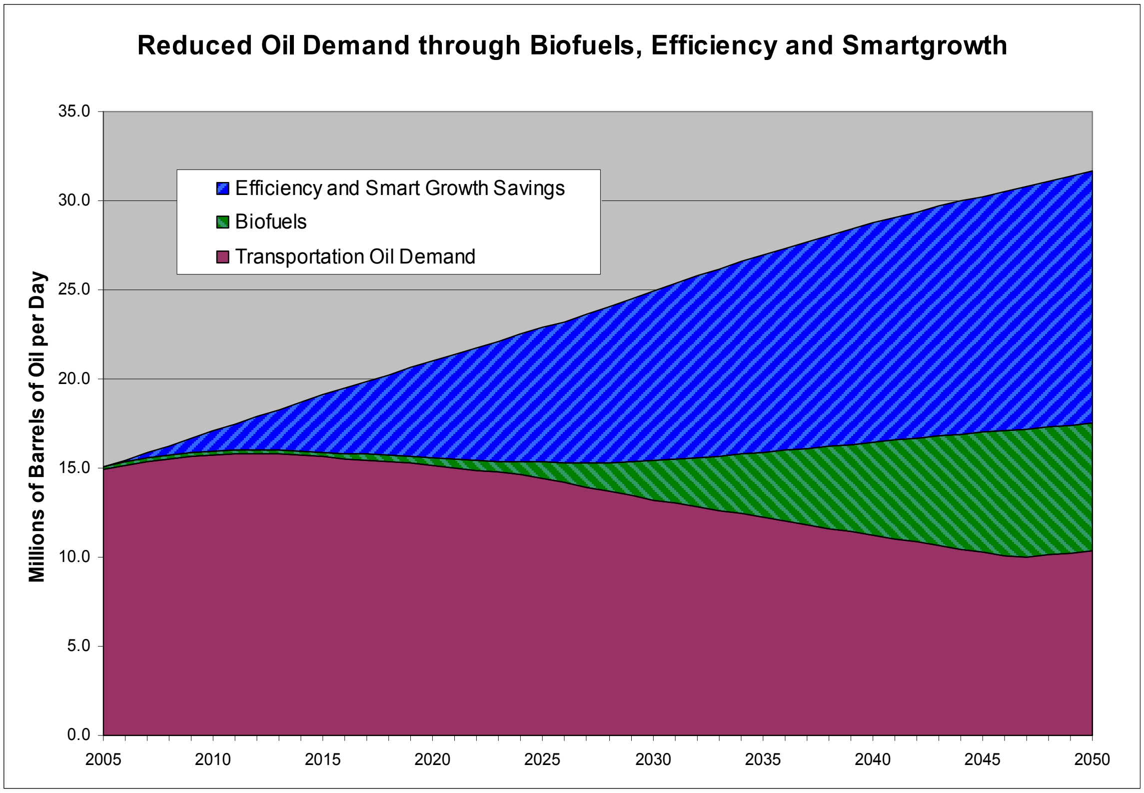


Figure 9. Reducing Oil Dependency through Efficiency, Smart Growth, & Biofuels

Figure 9 shows how we get from our current demand to this safer, cleaner, and more prosperous future. Notice the effect of limiting the amount of land available to biofuels. Without the restriction on land, we could produce an additional 22 billion gallons of ethanol, 2 billion gallons of Fischer Tropsch gasoline, and 2 billion gallons of Fischer Tropsch diesel. This would give us the equivalent of 118 billion gallons of gasoline and 12 billion gallons of diesel. This is actually more gasoline then we would actually demand after efficiency and smart growth measures are in place.

BIOFUELS AND CARBON CAPS

There is growing consensus about the need for mandatory limits on emissions of global warming pollution. Recently the Senate came just seven votes shy of passing the McCain-Lieberman Climate Stewardship Act, which would have imposed such limits through a cap and trade system. Under such an approach, sources of greenhouse gas emissions would be required to hold allowances in proportion to their emissions. The allowances would take on a value equal to the cost of reducing emissions. While the future price of carbon is uncertain, we have examined a range of likely carbon allowance values in order to get some insight into the impact that such a policy would have on biofuels.

The McCain-Lieberman Climate Stewardship Act approach requires refiners to hold allowances for the carbon content (and thus emissions from combustion) of their petroleum products. (Fossil fuel emissions from other large electricity and industrial sources are also regulated.) This will make the carbon allowance price an integrated cost of fuel production. So for instance, according to the analysis presented earlier, reformulated gasoline results in the emissions of the equivalent of 0.0127 ton of CO_2 on a life cycle basis. Everything else being equal, at $5 per ton, these emissions would increase the cost of this gasoline by $0.06 per gallon, and at $30 per ton this goes up to $0.38 per gallon.

The emissions accounting of petroleum fuels under the McCain-Lieberman bill means that the carbon content of biofuels is not regulated. This makes the implicit assumption that the growth-harvest cycle for biomass has no net carbon emissions. At the same time, the coverage under the carbon cap of electricity and fossil fuel use means that the relative differences between gasoline and diesel and biofuels should all be captured through the cost of inputs such as fertilizers made from fossil fuels. As a result, we would expect corn ethanol to see a very slight reduction in costs (about $0.01 between $15 and $30 per ton) and cellulosic ethanol to see a reduction about equal to the increase that gasoline sees. Thus for cellulosic ethanol the price impacts of a carbon cap and trade system could potentially be very significant, providing a nearly $0.40 price spread at $15 per ton of CO_2. We also expect that climate legislation will include direct incentives for the production of renewable energy, though these incentives are not captured here.

Table 22. Impacts of a Carbon Cap on Biofuel Prices

	GHG emissions (tons CO_2 equiv per gallon gasoline equiv)	Impact per gallon based on different values of CO_2 ($/ton)		
		$5	$15	$30
RFG	0.0127	$0.06	$0.19	$0.38
Corn Ethanol	-0.0003	($0.00)	($0.01)	($0.01)
Cellulosic Ethanol[a]	-0.0139	($0.07)	($0.21)	($0.42)
FT Gasoline[a]	-0.0139	($0.07)	($0.21)	($0.42)
Diesel	0.0141	$0.07	$0.21	$0.42
FT Diesel[a]	-0.0155	($0.08)	($0.23)	($0.47)

[a] These values are based on the EtOH/FT/GTCC configuration GHG displacement rate.

RECOMMENDATIONS FOR MAKING BIOFUELS OIL SAVINGS A REALITY

By focusing on innovation and change, this study takes an approach different from any before it. As a result, we have identified sustainable and cost-effective ways for biofuels to play a central role in dramatically reducing the oil dependency of our transportation sector. Potential on this scale deserves an effort at least as large and focused as we have proposed.

We have identified three key steps to realizing the promise of biofuels: 1) investing in research, development, and demonstration, 2) offering incentives for building biofuels processing facilities, and 3) adopting a renewable fuels standard along with a flex-fuel vehicle requirement. These measures can unlock the technological potential of biofuels, drive the cost down to the point where biofuels are cost-competitive with gasoline and diesel, and make these fuels available to all.

We have also identified the importance of the agricultural and environmental communities working together. The first step in this collaboration must be for each community to recognize the central issues and concerns of the other and for each community to commit to addressing these concerns. Working together, these nontraditional allies could keep our country's commitment to biofuels focused and consistent, ensuring that we capture all of the benefits of biofuels as soon as possible.

In the end, though, it will take more than just farmers and environmentalists. Biofuels, efficiency, and smart growth will create new opportunities for many industries from chemical companies though biotechnology to auto manufacturers, and the lower fuel costs and improved environmental conditions will benefit everyone. The key to delivering on the promise of biofuels is to start now.

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ENDNOTES

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[1] USDOE 2004b.
[2] USDOE 2004a.
[3] Abt 2000.
[4] USEPA 2004a.
[5] USDOE 2003a.
[6] Analyses of potential crop production area and economic gains at various crop prices have been conducted for this project using an econometric model called POLYSYS. The model was developed by a multi-institutional team to aid in evaluating the potential economic implications of bioenergy crops on U.S. agricultural policy. For more discussion of this model, please see De la Torre Ugarte 2002.
[7] The baseline is based on USDA price forecasts including USDA's assumption of increasing markets for exports. Absent the market for exports, switchgrass is even more helpful to farmers.
[8] In 2003, the U.S. consumed over 39 billion gallons of diesel and over 134 billion gallons of gasoline. Combined this amounts to over 173 billion gallons of fuel per year. USDOE 2003a.
[9] EIA 2003 and USEPA 2004a.
[10] Abt 2000.
[11] USEPA 2004a.
[12] While we have not focused on it here, rather than having RDD&D funding going from these levels to zero, a ramping down of funding after 2012 would continue to produce valuable results and also ensure continued investment by the RD&D community throughout the crucial 2006 to 2012 period.
[13] For a discussion of efficacy insurance in the context of assisting coal gasification technology, see DTI 2000.
[14] There are other challenges with offering efficacy insurance that would need to be addressed to make it an effective incentive. For the policy to be valuable to financiers, it would need to pay on very short notice so the project did not default on the loans. The risk of protracted legal battles with an insurance company would greatly diminish the value of the incentive.
[15] We recommend that eligible technologies be limited to biological conversion and thermochemical conversion with at least 50 percent of product in the form of motor vehicle fuel or electricity. Only energy products should be counted toward the capacity limits, and all energy products should be measured on a Btu (lower heating value) basis.
[16] One option would be to scale the life cycle greenhouse gas, oil displacement, and other environmental impacts so that each biofuels-technology combination would receive a score between 0 and 1 for each of these metrics. For greenhouse gases and oil displacement 0 would be no positive impact and 1 would 100 percent reduction relative to the petroleum alternative. For other environmental impacts, 1 would be at least maintaining current performance in terms of air, water, soil, and habitat quality, and 0 would represent a negative impact on all of these mediums. The greenhouse gas and oil scores could then be added and the sum multiplied by the environmental impact score. Such an approach would focus attention on greenhouse gas and oil displacement while environmental impacts a sort of veto of a biofuels-technology package.
[17] Walsh 1999.
[18] For these purposes it is generally blended with gasoline at a less than 10 percent mix.
[19] Chum 2003.
[20] Merrow 1981.
[21] Barnsby 2002.
[22] Plant breeding today increasingly takes advantage of a process known as genetic marking, in which genes native to a plant are marked so that their presence in future generations of the plant can quickly be identified. This speeds the process of selective breeding but does not introduce foreign genes into a plant.
[23]
[24] Burton 1982 and Burton 1998.
[25] Tollenaar 1989.
[26] Map provided by Daniel De la Torre Ugarte for the RBAEF study. The map includes improved yields for all crops over time. The regions on the map are agricultural statistical districts and are widely used to analyze the agricultural markets.
[27] Lynd 1996.

[28] The modeling discussed here relied on ALMANAC. ALMANAC is a physiologically based crop production model designed to quantify key plant-environment interactions that influence productivity and resource use by a wide variety of agricultural crops (For more information see Kiniry, J.R., Williams, J.R., Gassman, P.W., Morrison, M. et al., "A general process –oriented model for two competing plant species," *Trans*. ASAE 35:801-810, 1992.). Parameterization of ALMANAC for estimating switchgrass productivity at widespread locations in the United States was based on previous work with Alamo switchgrass at several sites in Texas (Please see Kiniry, J.R., Sanderson, M.A., Williams, J.R., Tischler, C.R., Hussey, M.A., Ocumpaugh, W.R., Read, J.R. Van Esbroek, G.A., and Reed, R.R, "Simulating Alamo switchgrass with the ALMANAC model," *Agron*. J. 88: 602-606, 1996.). Typical application rates from Mann 2000.

[29] Mann 2000.

[30] This is because annual harvesting allows the plant to slough off part of its root base and then regrow it the following season as the plant tries to keep its above and below ground portions in balance. The dead root base becomes soil carbon.

[31] McLaughlin 2002.

[32] Paine 1996.

[33] USDA 2004.

[34] Sheehan 2003.

[35] De la Torre Ugarte 2003.

[36] This assumes a baseline transportation diesel demand of 127 billion gallons in 2050 and a demand of 91 billion gallons with improved efficiency measures.

[37] This calculation is based on an energy density for crude oil of 130,000 Btu per gallon or 5.76 GJ per bbl and an energy density for switchgrass of 7,360 Btu per pound or 15.53 GJ per ton.

[38] Lynd 2004 and VanWalsum 1998.

[39] Two examples from just last year of successes in the biotechnology and pharmaceutical industries overcame challenges at least as big as those facing CBP. The first involved introduction into yeast of a completely foreign biosynthetic pathway for hydrocortisone production. The second developed yeast cells that produce recombinant proteins that have attached sugars typical of human proteins rather than yeast proteins. The project took less than three years to complete.

[40] Theoretically, the electricity produced from biomass could be used to produce hydrogen, but the combined efficiency losses and costs make this an unattractive option. A more efficient option would be to simply further refine syngas to remove contaminants and increase the hydrogen concentration.

[41] The synthesis of fuels or chemicals from gasified biomass will typically involve reactions under pressure that are driven by the partial pressures of the CO, H_2, and other reacting species in the gas. Inert nitrogen, which would be present in a gas from an air-blown gasifier, is a diluent that would reduce the partial pressures of the reacting species and lead to lower synthesis rates. Moreover, fuels and chemicals production will often involve separation, recompression, and recycle of unconverted gas back to the pressurized synthesis reactor (due to low single-pass conversion rates). The energy penalty and added equipment cost associated with separating and recycling large amounts of nitrogen and other inert compounds will be substantial.

[42] With oxygen gasification, the volumes of gas that must be accommodated (and hence sizes/costs of reactors, compressors, piping, etc.) will be considerably smaller than with air gasification. Since there are added costs for generating oxygen, below a certain size of plant it will be more attractive to use air-blown gasification. At the plant scales of interest in this report, the added cost of oxygen will be more than offset by the cost savings that are achieved by smaller equipment sizes.

[43] Lau 2003.

[44] Lau 2003.

[45] Sydkraft1998 and Sydkraft 2001.

[46] Paisley 2002 indicates that up to 90% tar conversion has been achieved in tests with the BCL technology at the Burlington, Vermont, pilot plant site. Stevens 2001 states that dolomite in an external tar cracker can remove 95 to 99 percent of tars from a gas stream at 750-900^{o}C. Finally, Bergman 2002 describes a new catalytic tar cracking system ("OLGA") that cracks essentially all tars.

[47] Oil palm uses one-seventh the land to produce the same amount of oil as does soybean, and oil palm is even more efficient compared to rape and sunflower. In addition, the Southeast Asia area where oil palm grows prolifically is particularly in need of the economic activity that expanded oil palm production would provide. For further information, see Fairhurst 2004, and these websites:

http://www.cyberlipid.org/glycer/glyc0051.htm and http://www.ppi-ppic.org/ppiweb/seasia.nsf/$webindex/DE5BCAF06FFCBBE848256D3D000856CF.

[48] Dale 1983.

[49] These calculations are based on plants that process between 5,000 and 10,000 dry tons of biomass per day; sell electricity at $0.04 per kWh; and have a 60/40 debt equity ratio, a 7.5% loan rate, and a 15% return on equity.

[50] Ensminger 1978.

[51] Pirie 1978.

[52] Pirie 1978, Dale 1981, and De la Rosa 1994.

[53] Ensminger 1978 and Dale 1981.

[54] Pirie 1978.

[55] There is some history in the corn ethanol industry of wastewater treatment facilities being undersized, resulting in biological oxygen demand problems because of wastewater discharge. These were problems of poor design and not technology and fortunately have been largely remedied in more recent plants. Corbus 1996.

[56] USDOE 1998.

[57] 7,332 kg/hr from a 5,000 ton/yr facility.

[58] Boerrigter 2002.

[59] See website at www.choren.de.

[60] USDOT 2002.

[61] (S&T)2 2002.

[62] This is based on the UCS modeling done for this report, which puts 2004 light-duty vehicle gasoline demand at 127 billion gallons and flex-fuel vehicle demand at 3.5 billion gallons.

[63] USEPA 2004b.

[64] USEPA 2004b.

[65] For example, passenger car horsepower has increased 73 percent since 1984.

[66] Ward's 2003.

[67] NRC 2001, Weiss 2000, Langer 2004.

[68] UCS calculation assuming a 5 percent real discount rate, similar to current automobile financing loans, 15-year vehicle lifetime, $1.40/gallon national gasoline fuel price, and 10 percent rebound effect.

[69] Sinor 1993.

[70] NRC 1996 and USEPA 1999.

[71] An extensive body of literature is available on these effects. See for instance: Dockery 1993, Pope 1995, and Health Effects Institute 2000.

[72] NESCAUM 2001a.

[73] NESCAUM 2001b.

[74] For more on permeation VOC emissions see CARB 2004a. For information on the apparent solution see NESCAUM 2001a.

[75] The cancer unit risk estimate is defined as the increased lifetime cancer risk caused by continuous lifetime exposure of a 1.0 microgram per cubic meter increase in the concentration of a given pollutant. As such it is useful here primarily for comparing the relative risk factor from each pollutant. These values are from CARB 2004b.

[76] Alleman 2002.

[77] For more background on Fischer Tropsch diesel see Clark, N., M. Gautam, D. Lyons, C. Atkinson, W. Xie, P. Norton, K. Vertin, S. Goguen, and J. Eberhardt, "On-Road Use of Fischer-Tropsch Diesel Blends," SAE 1999-01-2251, presented at Government/Industry Meeting, Washington DC, April 26-28, 1999. See also Norton, P., K. Vertin, B. Bailey, N.N. Clark, D.W. Lyons, S. Goguen, and J. Eberhardt, "Emissions from Trucks Using Fischer-Tropsch Fuel," SAE 982526, International Fall Fuels and Lubricants Meeting, San Francisco, 19-22 October 1998. For more background on DME see Fleisch, T.H., and P.C. Meurer, "1995: DME: the Diesel fuel for the 21st Century?" presented at AVL Conference on Engine and Environment, Graz, Austria, 1995. See also Fleisch, T.H., A. Basu, M.J. Gradassi, and J.G. Masin, "1997: Dimethyl ether: a fuel for the 21st century," Natural Gas Conversion IV, de Pontes, M., R.L. Espinosa, C.P. Nicolaides, J.H. Schotz, and M.S. Scurrell, eds., *Studies in Surface Science and Catalysis*, 107: 117–125 1997.

[78] NESCAUM 2001a.

[79] NESCAUM 2001c.
[80] NESCAUM 2001c.
[81] Design and evaluation of all biorefinery scenarios have been performed using ASPEN Plus simulation software, a process modeling tool for steady state simulation of material and energy balances.
[82] Lynd 2002.
[83] USDOE 2004c.
[84] For example, see Marrison, C.I. and E.D. Larson, "Cost Versus Scale for Advanced Plantation-Based Biomass Energy Systems in the U.S.," *Proceedings: The 1995 Symposium on Greenhouse Gas Emissions and Mitigation Research*, Sec. 4:26, 49, EPA/600/R-96/072, US Environmental Protection Agency, Washington, DC, June 1996.
[85] Note that in our configuration, the protein is actually produced in two stages, with the first and larger stage having a better balance of proteins. Thus we have assumed that this first fraction gets the full $0.20 per pound, while the second, smaller fraction gets only $0.15 per pound to account for the cost of proteins that would need to be purchased to achieve the desired balance.
[86] The key financial parameters on which these numbers are based include: debit/equity ratio of 40/60; loan rate of 7.5 percent; return on equity of 15%; discount rate of 12 percent; federal & state tax rate of 39 percent; property taxes & insurance rate of 1.5 percent; economic life of 25 years; depreciation period of 20 years; MACRS depreciation method; capital charge rate of 17 percent.
[87] These calculations assume the current U.S. mix of fuel for electricity generation, though the results do not change much with different fuel mixes.
[88] Interlaboratory Working Group 2000.
[89] RFA 2004.
[90] Motor gasoline and refinery capacity data are from USDOE 2003a.
[91] USDA 2003. Note also that perennial grasses, including switchgrass, are the primary crop currently grown on Conservation Reserve Program lands.
[92] These numbers are based on USDOE 2003a, but EIA's numbers have been adjusted to remove efficiency gains that EIA projects the market will achieve on its own. The past two decades provide ample evidence that vehicle efficiency is unlikely to improve absent policy intervention in the market. Therefore we have removed the efficiency gains that EIA projected.
[93] Light-duty vehicle fuel economy and performance are simulated using the Modal Energy and Emissions Model (MEEM), a comprehensive vehicle power-demand model, to capture the synergistic and overlapping effects of various technologies when they are applied to a vehicle alongside one another. MEEM predicts modal fuel use during the course of a defined test cycle by using a set of vehicle operating parameters to simulate vehicle power demand and operating conditions. See NCHRP 2001.
[94] Monahan 2004.
[95] For details, see Friedman 2003 and Lipman 2003.
[96] Ward's 2004.
[97] Hybrid vehicle market shares through 2015 are based on USDOE 2003a.
[98] Langer 2004.
[99] Ewing 2001.
[100] USEPA 2001.
[101] Holtzclaw 2002.
[102] Nelson 2000.
[103] Northwest Environment Watch 2002.
[104] Northwest Environment Watch 2002.
[105] Northwest Environment Watch 2002.
[106] PDAC 1996.
[107] The fact that no fuel price change was assumed is important for the present work since it allows us to vary the cost of driving, which is in part a function of efficiency, and model its effect on VMT independently of the Car Talk (PDAC 1996) VMT reductions.
[108] Jordan 2002.
[109] Sierra Club 1999.