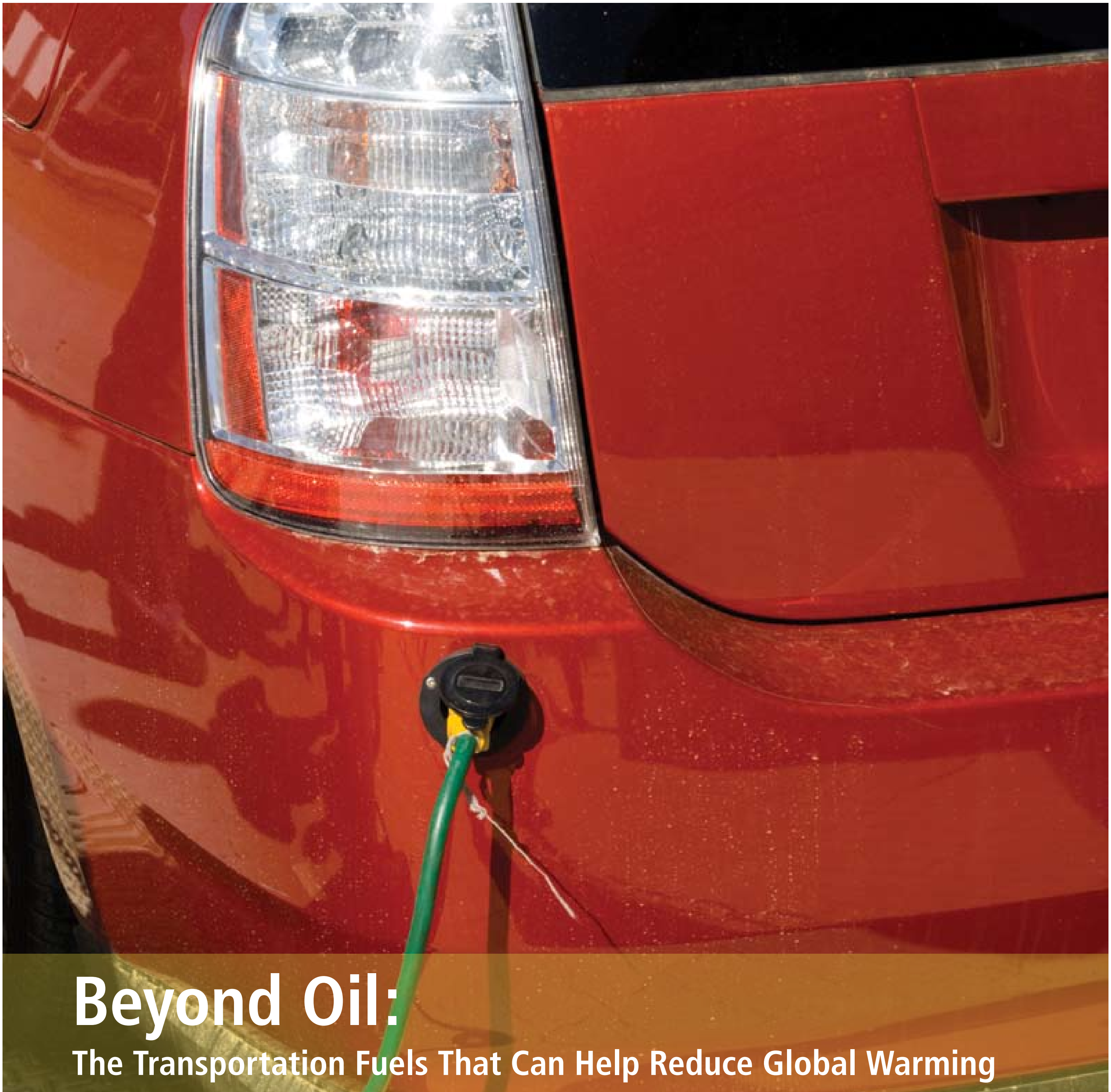

# Beyond Oil:

## The Transportation Fuels That Can Help Reduce Global Warming

Environment America Research & Policy Center

**July 2008**

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# Acknowledgments

Environment America Research & Policy Center thanks Nathanael Greene of the Natural Resources Defense Council and Eric Skelton of Northeast States for Coordinated Air Use Management for their insightful review. Thanks also to Tony Dutzik and Sarah Payne of Frontier Group for technical and editorial assistance.

This report is made possible with funding from the Energy Foundation.

The opinions expressed in this report are those of the authors and do not necessarily reflect the views of our funders or those who provided editorial review. Any factual errors are strictly the responsibility of the authors.

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# Executive Summary

The growing threat of global warming, air and water pollution, and rising energy costs are a few of the many problems that result from our current over-reliance on petroleum-based transportation fuels. Alternative transportation fuels, in conjunction with an array of other energy-related strategies, have the potential to help mitigate these problems—if public policy prioritizes those fuels that can deliver the greatest benefit for the environment and the American people.

**America's dependence on oil for transportation causes massive environmental impacts.**

- Emissions from transportation accounted for 33 percent of carbon dioxide emissions in the United States in 2005. Gasoline and diesel were responsible for 78 percent of transportation-sector emissions.
- Global warming is a growing threat to the environment and our way of life. Within a century, the average world temperature could increase by another 2 to 11.5°F. Sea level could rise by 7 to 23 inches, and snow and ice cover will continue to contract.
- Our heavy reliance on petroleum-based fuels has also created widespread air and water pollution.

**Alternative transportation fuels can reduce our dependence on petroleum, but vary greatly in their impact on the environment.**

***Corn-based ethanol*** has greater lifecycle global warming emissions than gasoline, when produced at the high volumes forecast for coming years and in ways that increase demand for cropland worldwide. Corn-based ethanol can also contribute to air pollution problems if used in low-percentage blends in gasoline and may potentially trigger significant environmental impacts from increased farming.

***Cellulosic ethanol*** made from agricultural residues or from crops grown on abandoned or marginal cropland may achieve emission reductions with less environmental impact, but is still in the very early stages of development.

***Biodiesel*** is generally recognized to produce less air pollution than conventional diesel, but soybean-based biodiesel produces more global warming pollution than conventional diesel when it is produced in ways that increase demand for cropland worldwide. Oil crop production is land-intensive, spurring cultivation of new land and resulting in high emissions. Biodiesel made from waste oil is 98 percent cleaner than conventional diesel, but supplies are extremely limited.

***Electricity*** can be used to power "plug-in hybrid" vehicles and all-electric vehicles, both of which draw electricity from the power grid. Because electric motors are far more efficient than internal combustion engines, vehicles that use electricity almost always produce less global warming pollution than gasoline vehicles, even when the electricity used to fuel them is generated from coal. The benefits are even greater when vehicles are fueled with renewably generated electricity. However, few electric vehicles are currently available to consumers.

***Natural gas*** reduces air pollution and global warming pollution compared with gasoline vehicles. But natural gas fueling infrastructure is expensive and domestic supplies of natural gas are both finite and increasingly constrained.

***Hydrogen*** has long been touted as the transportation fuel of the future. But the environmental impacts of hydrogen depend greatly on how it is produced, and hydrogen-powered vehicles are still a long way from being available to American consumers.

***Coal-to-liquids*** fuels would vastly increase global warming pollution from transportation, while exacerbating environmental impacts from coal production. Even if emissions from coal-to-liquids plants are captured and sequestered underground, coal-to-liquids fuels are likely to be no better, in global warming pollution terms, than today's petroleum-based fuels.

Figure ES-1 provides a comparison of the global warming impacts of non-biomass alternative fuels. Emissions from ethanol and biodiesel, included in Figure ES-2, are based on future production at a higher volume that researchers assume would trigger worldwide shifts in land use patterns.

**Figure ES-1. Relative life-cycle global warming emissions of non-biomass alternative fuels**

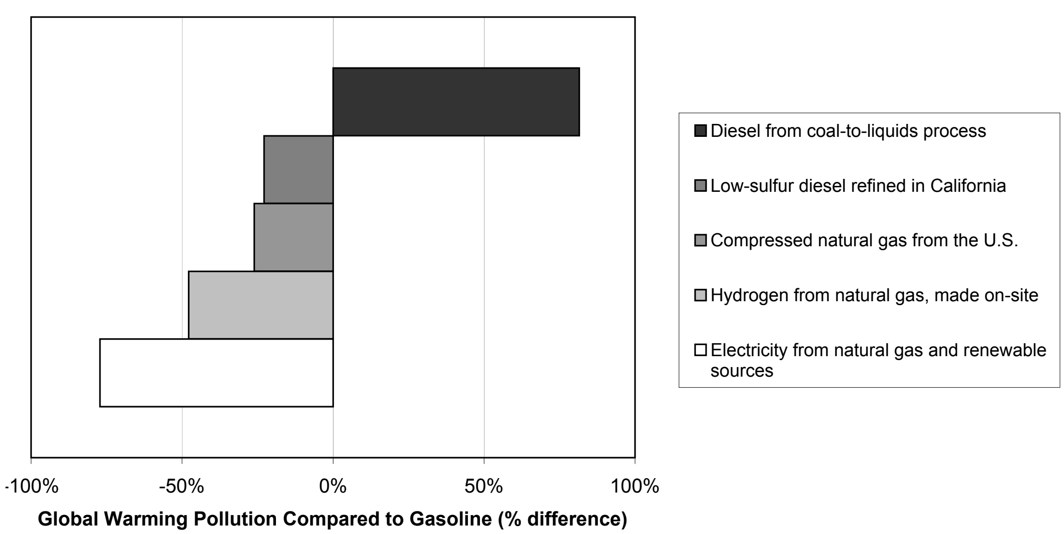
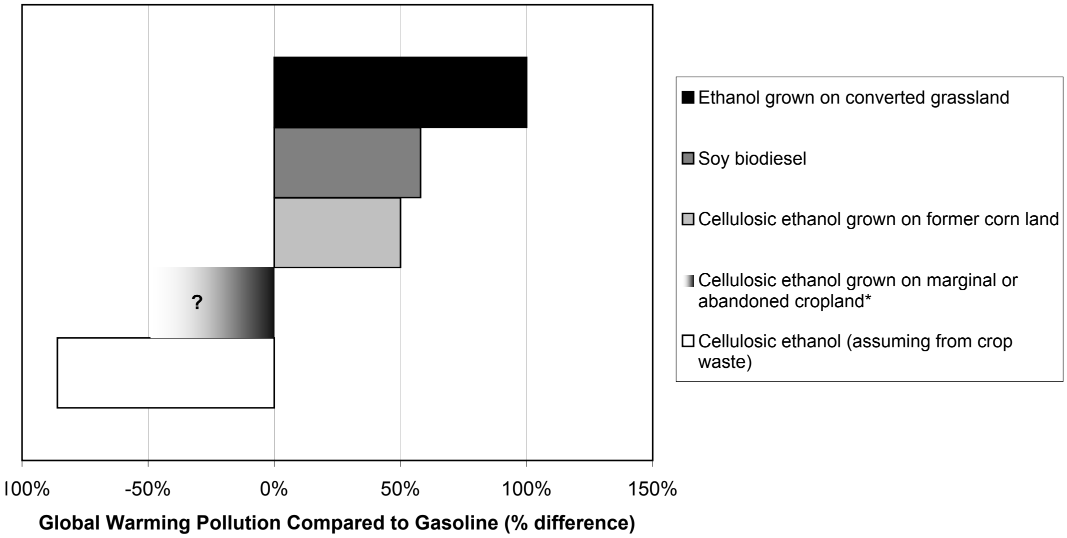


**Figure ES-2. Relative life-cycle global warming emissions of biomass alternative fuels at high production volumes**




* Data is not available on the full life-cycle emissions of cellulosic ethanol produced from feedstock grown on marginal or abandoned cropland, but such fuel has the potential for lower emissions than gasoline.

**America needs a comprehensive strategy to reduce global warming pollution from transportation. Low-carbon transportation fuels can play an important part in that strategy.**

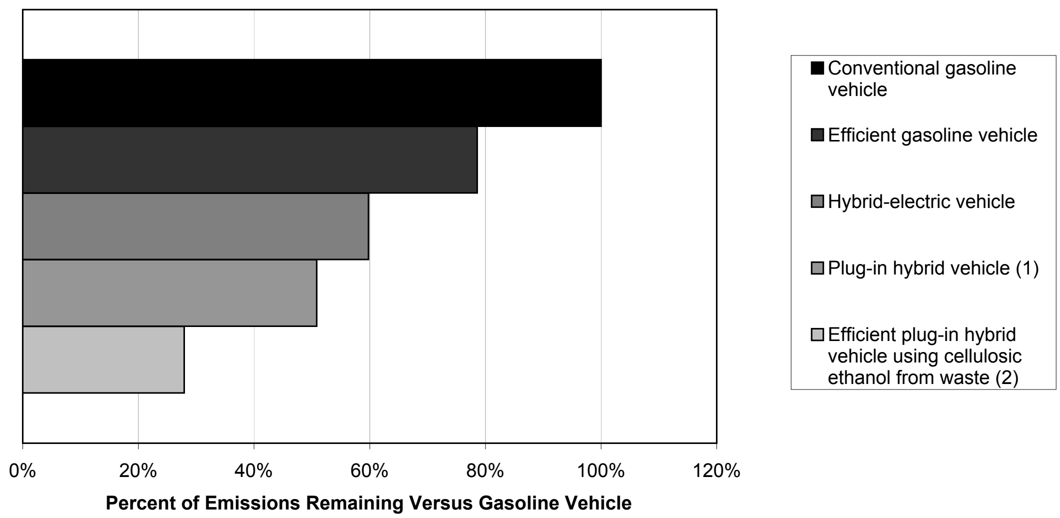
To reduce global warming pollution from transportation, America must reduce the amount of miles we drive, use more efficient vehicles, and shift to lower-carbon fuels. A low-carbon fuels strategy for the United States should:

***1) Combine the most promising approaches to maximize environmental benefits.*** America should work to make vehicles more fuel efficient, reduce liquid fuel consumption by increasing the use of electricity (in the short-term, through plug-in hybrids), *and* replace a significant share of the liquid fuel that remains with lower-carbon options. Such a comprehensive approach can slash per-mile global warming pollution from vehicles by as much as 74 percent compared to conventional gasoline vehicles.

***2) Develop fuels with long-term potential.*** Natural gas, for example, has the potential to reduce global warming pollution in the short term, but has little long-term potential as a transportation fuel due to limited domestic gas supplies. Some sources of cellulosic ethanol have comparatively lower life-cycle global warming emissions, but technological breakthroughs and infrastructure developments will be required before the fuel becomes widespread. Public policy should emphasize the development of infrastructure to support promising long-term fuel options over those with only short-term potential.

***3) Set stringent environmental standards and mitigate environmental and social impacts.*** America will be more likely to reduce the environmental impacts of transportation fuels if we set stringent environmental standards for those fuels. The first step should be to establish a low-carbon fuel standard that encourages the development

**Figure ES-3. Life-cycle emissions achieved by combining the best vehicle technologies and fuels**




(1) Vehicle is recharged with electricity that has the same carbon emissions as the U.S. national average.
(2) Cellulosic ethanol produced from crop waste. Electricity has same carbon emissions as U.S. national average.

of fuels with lower life-cycle global warming emissions. Standards should also be developed and implemented to mitigate the impacts of alternative fuels on the quality of our air, water and natural ecosystems.

***Achieving large reductions in global warming pollution from cars and light trucks in the years to come will require strong public policies. Necessary steps include:***

- Adopting requirements to lower the carbon content of transportation fuels and rejecting policies to promote fuels that would make the problem worse.
- Requiring that by 2020, all new vehicles are capable of using lower carbon fuels, whether electricity or biofuels.
- Supporting additional research into cultivation techniques for cellulosic feedstock and into technologies for converting cellulosic feedstocks, especially waste, into fuel.
- Improving vehicle fuel economy and pursuing measures to reduce total driving. These measures would further cut global warming emissions and reduce our vulnerability to rapid changes in the global petroleum market.

# Introduction

Americans are increasingly desperate to break their addiction to petroleum. Rising gasoline prices are costing consumers more at the pump and raising the price of food and manufactured goods. At the same time, our reliance on foreign oil leaves us increasingly vulnerable to economic and political instability abroad.

A desire for "energy independence" is one reason to reduce our consumption of oil. Global warming is another. The gasoline consumed in America's cars and trucks produces more global warming pollution each year than the entire economies of all but a handful of other nations. The most recent science tells us that we must slash global warming pollution immediately and dramatically if we hope to avoid the worst consequences of global warming. America cannot achieve that goal unless we reduce our consumption of oil for transportation.

These urgent twin imperatives of energy security and global warming are driving a search for alternative transportation fuels. There are a variety of candidates for the role of transportation fuel of the future, but no clear favorite has emerged.

One thing, however, is clear: America has little time to lose in addressing these challenges. And we cannot afford false starts.

As the race for alternative fuels accelerates, public policies should both encourage continued progress in developing new options and steer the development of new fuels toward options with the potential to reduce global warming pollution and avoid severe environmental impacts. Adoption of low-carbon fuel standards at the state or federal level can play a critical role in promoting fuels that benefit the climate and the environment and discouraging those that do not.

In this paper, we evaluate the leading contenders in the alternative fuels race, with a specific focus on their impact on global warming and the environment. By taking a creative approach that combines the best technologies, encourages the use of clean fuels, and sets rigorous environmental standards for alternative fuels from the very beginning, America can improve its energy security, while cutting global warming pollution and protecting our environment.

# Why We Need Alternative Fuels

There are many good reasons for America to break its addiction to oil. Consumption of oil for transportation has long caused its share of environmental problems. And now, with the serious consequences of global warming becoming more widely understood, the need to reduce oil consumption is even more urgent.

## Global Warming Pollution

Global warming threatens massive changes across the globe in the coming decades. Many of those changes have already begun to take place.

### Global Warming Is Already Happening

The first signs of global warming are beginning to appear throughout the world. Over the last century, global average temperatures have increased by 1.3°F.[1] Scientists believe that temperatures from 1950 to 2000 were likely the highest in the last 1,300 years.[2] Over the course of the 20th century, average sea level increased by approximately 6.7 inches worldwide.[3]

Snow cover in the Northern Hemisphere has declined over the last several decades, dropping by 5 percent during the 1980s.[4] Glaciers are retreating around the globe and the annual extent of Arctic sea ice has declined by 2.7 percent per decade since 1978.[5]

Worldwide, spring events—such as leaf unfolding, egg laying and bird migration—are occurring earlier in the year. In addition, numerous species of plants and animals appear to be moving toward the poles in response to rising temperatures.[6]

### Human Activities Are Causing Global Warming

There is scientific consensus that human activities are responsible for most of the global warming that has occurred over the last half-century.[7] Burning fossil fuels releases gases, such as carbon dioxide, that trap heat near the earth's surface, causing the planet to warm. Concentrations of carbon dioxide—the leading global warming pollutant—in the atmosphere have increased by more than one third since the beginning of the industrial age, and concentrations of other global warming pollutants have increased as well. (See Figure 1.) The concentration of carbon dioxide is higher now than it has been in the last 650,000 years.[8]

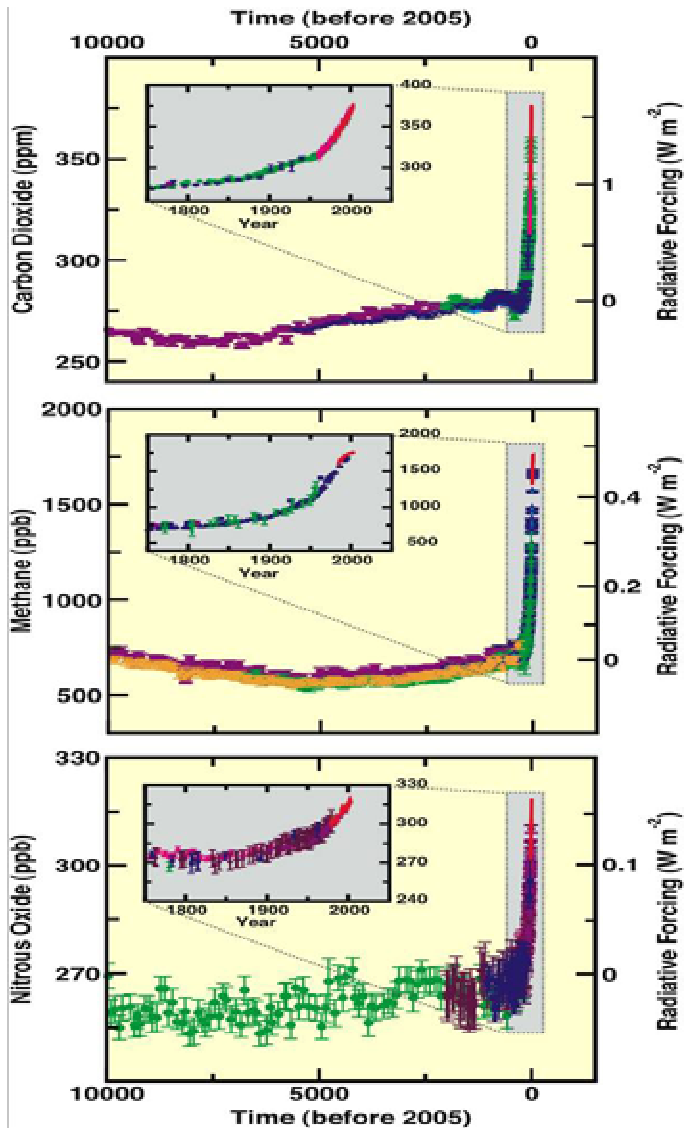
## What the Future Holds

Should emissions of global warming pollutants continue to increase, the world will experience dramatic warming over the next century and beyond, with major impacts on the environment, the economy and on human health.

The Intergovernmental Panel on Climate Change (IPCC), the world's leading authority on the science of global warming, recently updated its projections about the future course of global warming. The IPCC found that temperatures could increase by another 2 to 11.5°F above late 20th century levels by the end of this century, with the size of the increase depending on future emissions of global warming pollutants.[10] Sea level could rise by another 7 to 23 inches over the next century, with the level of rise again dependent on future emissions. These estimates do not include the potential for accelerated breakup of the Greenland or Antarctic ice sheets, which would cause a more dramatic rise in sea level.[11]

In short, global warming poses a severe threat to the future of the world's environment, its economy, and human health and welfare.

**Figure 1. Atmospheric Concentrations of Global Warming Pollutants[9]**

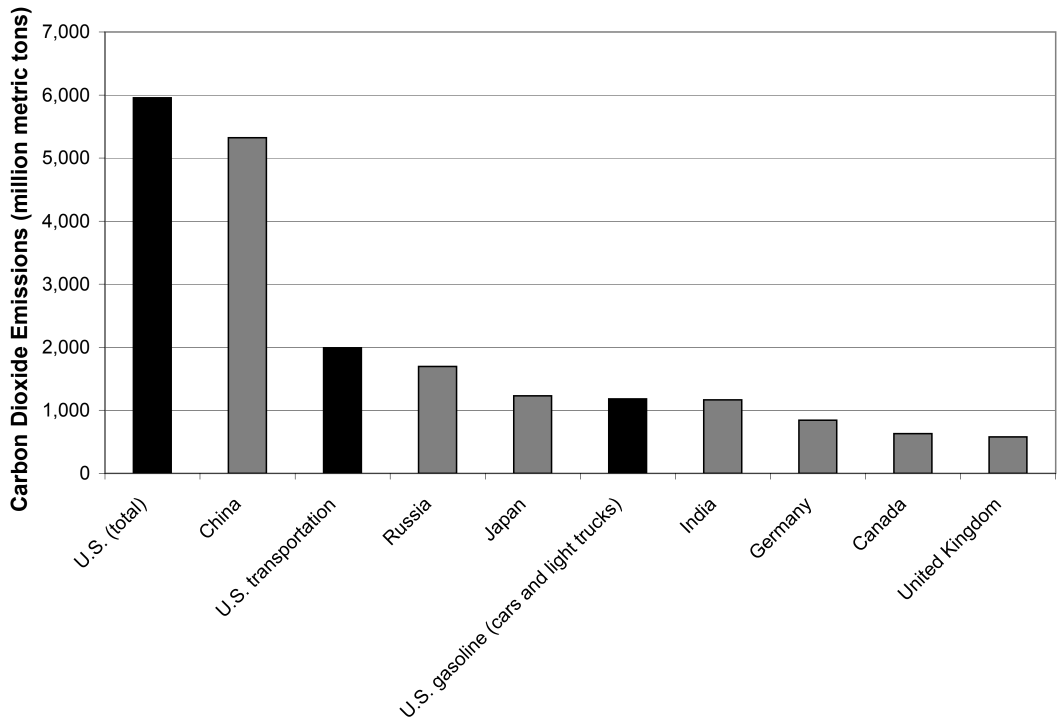



## Emissions from the Transportation Sector

The transportation sector (including personal travel in cars, light trucks and SUVs; freight shipping by truck and train; and airplane travel) is responsible for 33 percent of carbon dioxide emissions in the United States.[12] Only electricity generation, much of which relies on carbon-intensive coal, results in greater global warming emissions.

In 2005, the United States was responsible for approximately 22 percent of the world's emissions of carbon dioxide, the leading global warming pollutant.[13] As a result, our transportation system produced more carbon dioxide than *the entire economy* of any nation in the world, other than China.[14] Emissions from U.S. transportation gasoline use (the vast majority of which fuels cars and light trucks) were greater than those from any nation's economy except for China, Russia and Japan. (See Figure 2.) (Full emissions data for 2006 and 2007 are not yet available.)

## Figure 2. Carbon Dioxide Emissions, 2005[15]




The magnitude of emissions from the transportation sector means that any plan to achieve meaningful reductions in global warming pollution must include transportation. An approach that eliminated all emissions from the electric sector without touching transportation-sector pollution would leave total emissions in the U.S. higher than those from any country other than China. Curbing emissions from the transportation sector will require a multi-faceted approach, including improving the efficiency of vehicles, reducing how much Americans drive by offering transportation alternatives, and lowering the carbon content of fuels.

# Other Pollution from Petroleum Use

The production, refining and use of petroleum damages ecosystems and causes air and water pollution.

## Air Pollution

Oil refineries emit cancer-causing chemicals that present a threat to workers and nearby residents. The chemicals include benzene, formaldehyde, and polycyclic aromatic hydrocarbons (PAHs). Benzene and formaldehyde are known to cause cancer in humans, while PAHs are suspected carcinogens. The petroleum industry was responsible for more than 50 percent of the nation's total "fugitive" emissions of benzene in 2005, for example.[16] Total emissions of benzene in the United States are high enough to cause 10.5 more cases of cancer per million people each year than would otherwise occur.[17] The combustion of gasoline and diesel in vehicles releases many of the same chemicals as come from refineries.

The use of petroleum products creates particulate matter pollution and contributes to smog. Particulate matter can penetrate deep into the body, carrying chemicals that cause cancer, irritate lung tissues, and change how the heart functions.[18] Exposure to particulate matter also is suspected to depress immune function, increasing susceptibility to other disease.[19] As a result, particulates cause and aggravate a host of health problems, including lung cancer and cardiovascular disease. Smog, or ground-level ozone, can irritate sensitive lung tissue, impair lung development in children, and increase the risk of developing asthma.

### Water Pollution

Oil spills from drilling rigs, refineries, tankers, pipelines and storage tanks can result from carelessness, accidents and rough weather. Spilling even a small amount of oil can contaminate large volumes of drinking water, surface waters or the ocean.

The 1989 Exxon Valdez spill in Alaska was the largest oil spill in U.S. history, but many smaller spills occur each year, causing damage to wildlife and ecosystems. In 2005, hurricanes caused 43 oil spills in the Gulf of Mexico.[20] In 2007, a cargo ship collided with the Golden Gate Bridge in San Francisco and released 58,000 gallons of oil.[21]

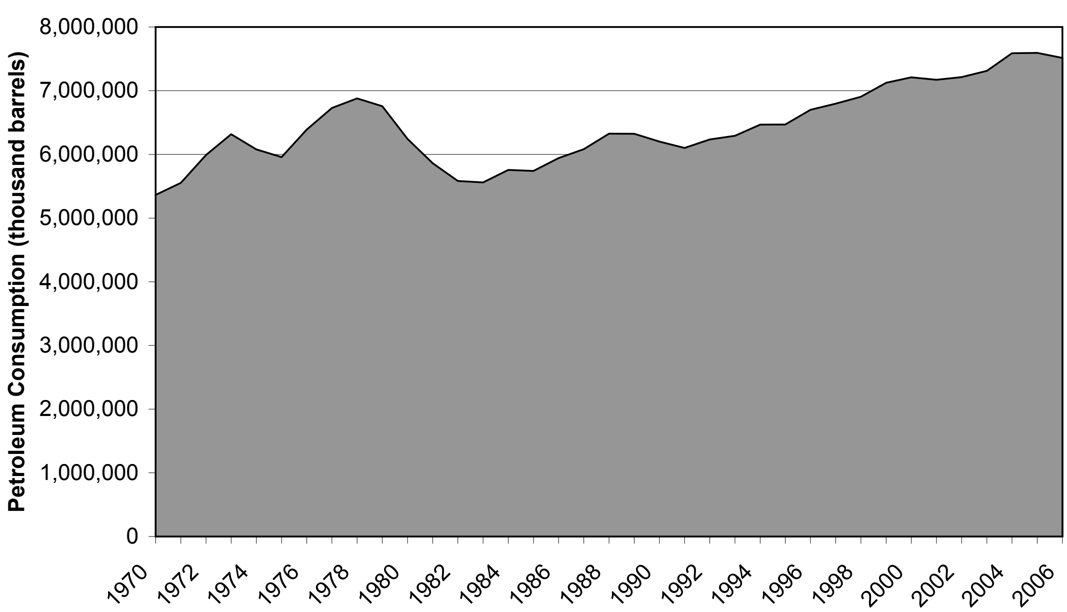
Reducing gasoline and diesel use will mean less oil-producing infrastructure and fewer opportunities for releasing oil into the environment.

## Energy Insecurity

The environmental impacts of oil production and use are more than enough reason for the United States to take steps to reduce our consumption. But our dependence on foreign oil—and rising prices for that oil—present another set of compelling reasons to end our addiction to petroleum.

America is highly dependent on oil—particularly for transportation. The U.S. uses more petroleum for transportation than for any other purpose. In 2005, the transportation sector consumed 5.1 billion barrels of gasoline, diesel and other liquid fuels, or 67 percent of total oil consumption in the U.S.[22] Americans spent $364 billion on transportation fuels in 2004, of which more than three-quarters was for imported fuel.[23] With the recent increase

**Figure 3. Annual U.S. Petroleum Consumption[26]**



in oil prices, this level of spending is likely far greater today.

Demand for petroleum has grown in recent years, both in the U.S. and in industrializing nations. Figure 3 shows that petroleum demand in the U.S. has increased by 35 percent since the early 1980s, as the country recovered from the oil price shocks of the 1970s and the subsequent economic recession.[24] As the largest petroleum consumer in the world—the U.S. consumed 24 percent of the petroleum used in the world in 2006, compared to second place China at 9 percent—rising domestic demand has a large impact on world oil supplies.[25]

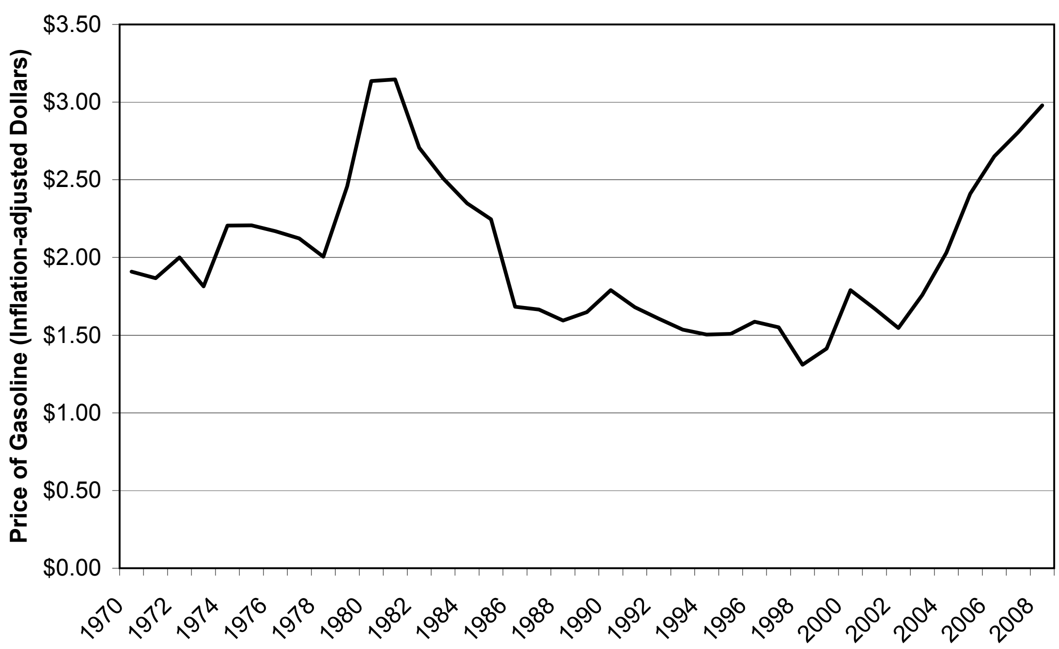
Rising demand for oil worldwide has led to higher prices. (See Figure 4.) One of the most immediate results for U.S. consumers is that the price of gasoline has doubled in the past five years.[27]

Oil production has not increased at the same rate as demand because worldwide oil supplies are limited, for technological and natural reasons. The equipment needed to drill, mine and refine oil is expensive, and producers have been unwilling to invest in new infrastructure in the face of energy markets made volatile by political unrest or storms that disrupt production. Nor can additional production capacity be brought on line quickly in response to consistently higher energy prices.

However, a larger problem underlies the lack of petroleum, and that is limited natural deposits of high quality oil in accessible locations. "Proved reserves" of oil, a figure that oil-producing countries and corporations have been known to overstate, are estimated at 1.2 trillion barrels.[29] That is only slightly more petroleum than the world has consumed since oil production began in the mid-1800s.[30] At the current rate of worldwide annual petroleum consumption—approximately 30.5 billion barrels of oil—all proved reserves would be consumed in the next 38 years.[31] Nearly 75 percent of these reserves are concentrated in just seven nations: Saudi Arabia, Iran, Iraq, Russia, Venezuela, Kuwait, and United Arab Emirates.

Growing demand coupled with limited supply that is increasingly concentrated in unstable parts of the world means that prices will continue to rise in coming years

**Figure 4. Historic Price of Gasoline[28]**



and that oil-producing countries will have opportunities to manipulate the price and availability of petroleum. Moreover, oil prices are notoriously volatile and could become even more so in the years to come, exacerbating the economic damage of our heavy reliance on petroleum.

## Options for Reducing Transportation-Sector Pollution and Petroleum Use

Reducing global warming pollution in the United States will require cutting pollution from all sectors of the economy, including transportation. To prevent the most dangerous impacts of global warming, we need to cut emissions by at least 15 to 20 percent by 2020 and by 80 percent by 2050. Such reductions are not possible without a broad approach that includes more efficient use of energy, and cleaner fuels, from wind and solar power to transportation fuels with a lower carbon content. Reducing emissions from just one or two sectors of the economy, such as electricity generation and industrial energy use, will not be sufficient to reduce pollution to levels sustainable over the long term. Changes in the transportation sector are essential to any pollution-reduction plan.

Global warming pollution from transportation and oil consumption can be reduced through three complementary approaches.

- The first element is to improve vehicle efficiency, such as with stronger fuel economy standards for cars and trucks.

- The second element is to reduce vehicle travel. Driving in personal vehicles can be reduced by encouraging transit, walking, or bicycling, by using carpools, and by finding ways to avoid trips altogether. Compact development—where shops, houses and services are within walking distance of each other—facilitates the use of alternative transportation and is crucial to reducing driving in the long term. Vehicle travel can also be cut by reducing how far freight must be shipped by truck or by using alternatives such as rail, which consumes less fuel per ton of freight shipped and thereby produces lower overall emissions.

- The third element is to use alternative fuels that contribute less to global warming.

To achieve the most dramatic results in reducing oil consumption, America must combine these three approaches. For example, a car that is 25 percent more efficient, is driven 25 percent fewer miles, and replaces 25 percent of its fuel with alternatives will consume 58 percent less oil. To obtain the same reduction from transportation sector emissions without any reduction in the carbon intensity of fuel would require a 35 percent reduction in driving and a 35 percent improvement in vehicle efficiency—both of which are possible, but more difficult to achieve.

Thus, though reducing the carbon intensity of fuels is not straightforward, it is an essential step to cutting emissions from the transportation sector.

In this paper, we focus specifically on the role that alternative transportation fuels can play in reducing the global warming impact of America's transportation system and our consumption of oil. In the following sections, we will briefly discuss the global warming and other environmental impacts of several alternative fuels and then discuss policy options for encouraging increased production and distribution of the best low-carbon fuels.

# Evaluating Alternative Fuels

Not all fuels that can replace gasoline or diesel have equal global warming, environmental or social impacts. A complete understanding of the impacts of each fuel is possible only through a life-cycle analysis, an evaluation of the effect of a fuel from the time a crop is planted for a biofuel or natural gas is drilled to generate electricity, all the way through to its final use in a vehicle. The best fuels are those that have the lowest life-cycle global warming emissions and create the fewest negative environmental and social side effects.

## Ethanol

Ethanol is a nearly pure grain alcohol produced from the fermentation of plant material, most frequently corn, sugar cane, or cellulosic material. The conclusion that ethanol use reduces petroleum consumption is generally accepted by researchers, but, depending on the feedstock, the substitution of ethanol for gasoline may not provide any global warming benefit.[33]

Corn ethanol production generally results in a fuel with greater life-cycle global warming pollution than gasoline. Cellulosic ethanol from crop waste and other sources with limited land use impacts has greater potential for lowering global warming emissions than corn ethanol, but it is not yet widely manufactured. Cellulosic ethanol is made from sugars trapped in plant stalks and leaves rather than in the nutritive portions of the plant, which can be freed from their chemical bonds using an additional processing step involving enzymes or acids. Currently there is no large-scale ethanol production from energy crops such as switchgrass or crop residues such as corn stalks and rice husks; with technological advances these feedstocks could become major sources of ethanol production in the future.

Sugarcane and sugar beets are a third crop source for ethanol, and sugarcane is commonly used for ethanol production in Brazil. However, the U.S. has a very limited capacity to produce ethanol from sugarcane and sugar beets. Sugar beets can be grown in more of the country than can sugarcane, but even if all sugar beets grown in the U.S. were devoted to ethanol production, the total ethanol produced would equal just 10 percent of current corn ethanol production.[34]

## Global Warming Impact

Like all biofuels, the global warming impact of ethanol is the result of the interaction of all the elements of its life cycle. However, the global warming pollution from some of those elements changes depending on the total volume of ethanol that is produced and how it alters global markets for food and other agricultural products. Until recently, corn ethanol had not been produced at large enough volumes to affect global markets. But with recent dramatic increases in ethanol production, and projections of future increases in years to come, it is important to consider its global impacts.

High-volume corn ethanol production does not result in lower global warming emissions than gasoline. In fact, full life-cycle emissions from corn ethanol may be twice as high as gasoline, when secondary land-use impacts are taken into account.[35] In contrast, producing cellulosic ethanol from certain feedstocks can reduce global warming pollution. Cellulosic ethanol made from crop waste or prairie grass grown on abandoned or marginal cropland can have emissions well below that of gasoline.

### Feedstock Production

Farming practices affect the amount of global warming pollution that results from a particular ethanol feedstock. Energy-intensive approaches and crops that require more fertilizer increase fossil fuel use and thus global warming pollution. Poor farming methods can result in the release of nitrous oxide and carbon dioxide from soil, both of which contribute to global warming.

The global warming impact of feedstock cultivation has two major elements: emissions from how the feedstock is grown on a particular farm and emissions from worldwide changes in land use practices as more acreage is dedicated to the cultivation of biofuel feedstocks instead of food.

#### *Direct Emissions*

Modern farming practices rely heavily on fossil fuels. Natural gas is used to make synthetic fertilizers, petroleum is an essential component of pesticide manufacturing, and diesel fuel powers the equipment needed for planting, spraying and harvesting crops. Thus, when a farmer can produce a bushel of corn with less fertilizer and less cultivation, global warming pollution may decline.

Reducing fertilizer use cuts global warming pollution by lowering consumption of natural gas necessary for making fertilizer and by reducing releases of nitrogen from soil. Nitrous oxide is a powerful greenhouse gas, nearly 300 times more potent than an equivalent amount of carbon dioxide. Excessive application of fertilizers intended to boost the amount of biologically available nitrogen in soil and thus increase yield can result in greater emissions of nitrous oxide from the soil.[36]

Reducing cultivation cuts both direct emissions from farm machinery and indirect emissions from soil. No-till farming or conservation tilling eliminates or reduces the need to turn over the soil repeatedly, thus curbing releases of carbon from the soil. Less tilling also has an additional benefit not related to global warming, which is that it reduces erosion.[37]

The net impact of these changes in farming practices can be substantial. Improvements in farming efficiency in the past several decades have increased yields of corn from less than 90 bushels per acre in the mid-1970s to nearly 150 bushels per acre now without a commensurate increase in pesticide and fertilizer use.[38] As a result, inputs per bushel harvested have declined, potentially reducing global warming pollution per gallon of ethanol produced from corn.

A key factor in emissions from feedstock production is the choice of crop. Cultivating cellulosic material such as switchgrass results in lower global warming emissions from agricultural practices compared to corn. Switchgrass can be cultivated with less fertilizer and pesticide, is better at retaining carbon in soil, causes less water pollution, and allows less soil erosion.[39]

Most importantly, cellulosic ethanol can be produced from crops grown on marginal or abandoned cropland. Restoring abandoned cropland by planting a mix of prairie plants including legumes and grasses increases the amount of carbon stored in the soil and in plant roots compared to

## Life-Cycle Analysis of Global Warming Emissions

Typically, when we think of air pollution from transportation, we think of emissions from a car's tailpipe. However, this does not account for the full extent of the global warming pollution from transportation. Drilling for oil, refining it into gasoline and transporting it to consumers all create pollution in addition to the emissions released directly from a vehicle's tailpipe. These emissions that occur before fuel is used in a vehicle are called "upstream" emissions.

With most light-duty vehicles in the U.S. currently operating on gasoline—and thus having roughly uniform upstream emissions—there has been little need for life-cycle analysis of pollution from various fuels. However, as alternative fuels enter the market—and as some of those fuels have greater "upstream" emissions than emissions at the tailpipe—life-cycle analysis becomes an important tool for evaluating the global warming impact of different fuels.

A comprehensive life-cycle evaluation includes global warming emissions from the following steps:

- **Producing or extracting feedstock.** For biofuels, this includes global warming pollution released when soil is disturbed by tilling, emissions from farm equipment and pollution from fertilizers. It also includes the benefit of carbon absorption by biomass. For fossil fuels, this includes emissions related to extracting crude oil, coal or natural gas from the ground.

- **Transporting the feedstock to the refinery.** Both the distance and the method of transport affect emissions.

- **Refining or conversion**. For biofuels, this includes the conversion of crop material into biofuels, including emissions from burning coal, natural gas or biomass to dry the feedstock and process it. For electricity, this step would include the combustion of fossil fuels to produce electricity.

- **Transporting the fuel to market.** Both the distance to market and the method of transport affect emissions.

previous use of the land.[40] Using marginal or abandoned cropland means that cellulosic feedstock production will have less impact on global food markets, which can trigger land use changes in other countries and increase emissions from biofuels, as discussed in the next section.

Cellulosic ethanol also can be produced from crop waste, which incurs much lower emissions from feedstock production.

***Worldwide Emissions***

The discussion in the preceding paragraphs focuses on emissions from land use and farming choices where the ethanol feedstock is grown. However, those choices are not the only land use decisions that affect emissions from ethanol. Secondary land

- **Consuming the fuel in the vehicle.** Carbon released by the burning of biofuels is counted here. This step also includes an adjustment for how much of the energy in the fuel is translated to propulsion. Electric motors, for example, are five times more efficient than gasoline engines.[32]

- **Secondary impacts**. Secondary impacts are the broader changes that occur when a new form of transportation fuel is used. For example, biofuels create secondary impacts in land use when one farmer replaces a wheat field with corn for ethanol, and a second farmer responds by turning pasture into a tilled field to grow wheat. These effects are complex and can occur around the world. Other secondary impacts include increased emissions from fertilizer production and reduced emissions from replacing animal feed with byproducts from ethanol production. Fossil fuels have secondary impacts as well. Increasing natural gas use in vehicles might result in increased demand and higher prices, which could encourage switching from natural gas to coal to generate electricity.

A comprehensive life-cycle analysis also allows for consideration of other environmental impacts from fuels, such as whether growing a biofuel encourages deforestation or other negative land use practices, whether processing biofuels strains water supplies, and if the fuel, when processed or burned, adds to air pollution. A final consideration is how demand for biofuels might compete with food uses of some crops.

Life-cycle analysis of the global warming pollution for transportation fuels includes a large degree of uncertainty. A comprehensive calculation includes all the factors discussed above, each of which is contingent upon multiple assumptions and complex interactions. The researcher also needs to decide what secondary and tertiary impacts should be included in the analysis. The result is that every estimate of the life-cycle emissions of different fuels includes a degree of uncertainty—sometimes very large. Nonetheless, the estimates that researchers have produced for different fuels are valuable for guiding public policy toward fuels with lower emissions, and as life-cycle analysis matures, we will have access to better and more refined estimates of the impacts of various fuels on the climate.

use changes—such as how the increased use of corn for fuel reduces exports of agricultural products including soybeans, wheat, and rice, thus prompting farmers elsewhere to clear more land for cultivation of food crops—are a major factor in life-cycle emissions from ethanol production, especially as demand for ethanol grows.

As U.S. farmers dedicate more of their corn crop to ethanol production, corn exports decline. Farmers in other countries respond to declining imports and rising prices by producing more corn or other food crops. Some corn may be produced on existing cropland, but those displaced crops still need to be produced. Ultimately, new land is cleared for cultivation.

Cutting down a forest or plowing up grassland increases emissions in several ways. First, those trees, grasses and other plants contain carbon that is released into the atmosphere as they decay or are burned as the land is cleared. Second, they no longer are available to absorb and store carbon. Finally, disturbing soil causes it to release approximately one-fourth of the carbon that it had absorbed.

The result of this worldwide shift in land use is greatly increased life-cycle emissions from corn ethanol production. Whereas researchers estimate that corn ethanol produces 18 percent less global warming pollution than gasoline if worldwide land use changes are not accounted for, adding those global shifts in land use raises ethanol's life-cycle emissions to approximately twice those of gasoline.[41]

The estimate that corn ethanol produces twice the global warming pollution of gasoline is based on a scenario in which the U.S. produces 30 billion gallons of ethanol in 2016. Even if production volume were lower, the impact of worldwide land use changes would still cause corn ethanol to have higher emissions than gasoline. The study's authors estimate that even if actual production in 2016 is 25 percent lower than

*The global impact of increased ethanol production and higher corn prices includes more deforestation and rising global warming pollution. (Credit: Mark Atkins, Dreamstime.com)* they postulated, emissions from worldwide land use change would decline by only 10 percent from the high-production scenario.[42]

Global land use decisions also have the potential to raise life-cycle emissions from switchgrass-based cellulosic ethanol. The scale of secondary land use changes on emissions can be seen from one life-cycle analysis model that examined the impact of growing switchgrass on land capable of producing corn. While this is a highly unlikely substitution that no farmer seeking to maximize profits would choose, the model suggests that it would cause life-cycle emissions of cellulosic ethanol to be 50 percent higher than gasoline.[43]

These are some of the first calculations that researchers have made of the global warming impact of indirect land use change from ethanol feedstock production. Newer and better data will become available about the indirect land use impacts of ethanol feedstock production as researchers create increasingly sophisticated models of worldwide changes triggered by biofuels production in the U.S.

Secondary land use change may not be of as much concern with cellulosic ethanol as for corn ethanol. Improved cultivation of cellulosic feedstocks may allow cultivation of crops for ethanol without requiring much new land.[44] Cellulosic feedstocks can be produced from abandoned or marginal cropland, which would trigger fewer, if any, changes in crop exports and overseas land use patterns. It may also become possible to increase production of cellulosic material as a byproduct of food production or through greater use of cover crops when land is not in use for food production. If this becomes possible, then life-cycle emissions of cellulosic ethanol could be much lower than gasoline.

Cellulosic ethanol produced from wastes does not trigger these indirect land use changes, and thus produces lower life-cycle emissions than gasoline.[45]

**Transportation to the Refinery**

Feedstock, whether corn or cellulosic material, must be transported from the field to a refinery or distillery. Emissions are lowest when the refinery is located close to where the feedstock is produced. In addition, transportation emissions usually are lower when the feedstock is moved by train rather than by truck. Moving freight by train rather than truck requires only one-third the amount of fuel and thus produces far less global warming pollution.[46]

**Refining**

Ethanol refining involves the fermentation of plant sugars or starches and subsequent distillation steps, typically in the presence of heat. Refineries can be powered by coal, natural gas or even biomass. The choice of fuel to generate heat plays a large role in determining the global warming impact of the ethanol.

To produce the same amount of heat, coal produces 89 percent more global warming pollution than natural gas.[47] Currently, most refineries use natural gas as their principal energy source. A switch to coal-powered production—attractive to refiners because of coal's lower prices—would result in ethanol with higher emissions than gasoline, even before the effects of indirect land use change are considered.[48]

Another factor affecting the carbon intensity of ethanol refining is how co-products are used. Refining creates co-products, such as distillers grains that can be used for animal feed and wastes that can be used as fuel. Lignin, found in plants used for cellulosic ethanol, cannot be fermented into ethanol but can be burned to create heat to power the refinery and even generate electricity to be sold into the grid.[49] These uses of co-products displace other processes—the manufacturing of animal feed or burning of fossil fuels for heat or electricity generation—that release global warming pollution. The savings can be credited to the life-cycle emissions from ethanol.

Were carbon sequestration ever to become a viable technology, the production of cellulosic ethanol from waste material could provide a means for reducing carbon dioxide levels in the atmosphere. Plants capture carbon from the atmosphere as they grow. Typically, that carbon is released again when the plant decays or is burned for energy. However, a refinery powered by waste biomass to produce cellulosic ethanol could capture its on-site carbon emissions and sequester them, thus effectively removing carbon from the atmosphere.

**Transportation to Market**

The life-cycle emissions of ethanol increase if the fuel must be transported a long distance from the refinery to consumers. This means that corn grown and refined in the state where it will be consumed as ethanol has lower life-cycle emissions than ethanol shipped to a distant market.

Shipping ethanol is more energy-intensive and thus produces more emissions than shipping gasoline the same distance. Ethanol is difficult to ship by pipeline, so it must be shipped by truck or rail, both of which are less efficient.[50] Furthermore, because ethanol has a lower energy content per gallon, a tanker truck loaded with ethanol delivers less energy to fueling stations despite having expended just as much fuel as if the tanker had been full of gasoline.

**End Use**

Ethanol can be consumed at low concentrations (typically 10 percent or less by volume) in conventional gasoline-powered vehicles. If the auto manufacturer has made a few small changes to a vehicle's engine, it can consume ethanol at concentrations up to 85 percent by volume. As with gasoline, a more fuel efficient car will require less energy and produce less pollution when traveling a given distance.

In summary, a multitude of factors determine life-cycle global warming emissions from ethanol. How the feedstock is produced, transported for refining, refined, transported to market, and consumed all influence emissions. The interplay of these factors, especially with worldwide agricultural land use, means that high-volume corn ethanol production results in a fuel with life-cycle emissions that are approximately twice that of gasoline.[51] Cellulosic ethanol from waste, which is cleaner because producing the feedstock releases fewer emissions, can be 95 percent less polluting than gasoline.[52] New methods of cultivating cellulosic feedstocks from marginal or abandoned cropland also could yield a fuel with much lower emissions than gasoline.

## Air Pollution

Though ethanol has clear potential to reduce global warming pollution, it may lead to greater releases of air pollution during the refining process and potentially during use in vehicles.

Increasing production of ethanol will increase air pollution near refineries unless adequate pollution control regulations are in place. Unfortunately, current standards for biofuel refineries are not very strong. The U.S. EPA conducted an analysis of the air pollution impacts of the ethanol provisions in the 2005 Energy Policy Act, which required that ethanol production be increased to 7.5 billion gallons.[53] (The 2007 Energy Independence and Security Act mandates a further increase in biofuel production to 36 billion gallons by 2022. Of the 36 billion gallons, 16 billion gallons must be cellulosic biofuel and an additional 6 billion gallons must be advanced biofuel that is not produced from corn.) The EPA concluded that emissions of volatile organic compounds (VOCs) will increase by as much as 732 tons per year in some counties with the largest ethanol refineries. Those same counties will experience increases in nitrogen oxide (NOx) pollution of 996 tons per year.[54] Both VOCs and NOx contribute to smog. Because most counties that are building new ethanol refineries already meet EPA air quality standards, EPA has indicated it will allow new plants. However, ozone likely is hazardous at concentrations lower than the legal air pollution standard and therefore new plants will create health impacts.

Ethanol, whether made from corn or cellulosic material, produces lower tailpipe emissions of some air toxins, such as benzene, though emissions of others, such as acetaldehyde, rise.[55] EPA estimates that under the requirements of the 2005 Energy Policy Act, benzene emissions will fall 1.8 to 4.0 percent and formaldehyde emissions will also decline.[56] This shift in the mix of emissions may or may not be a net public health benefit. Formaldehyde, which will decline, is a more potent toxin than acetaldehyde, but for vulnerable subgroups, acetaldehyde may prove more hazardous.[57] Better pollution controls in vehicles and in refueling infrastructure can address some of these emissions, but mixing ethanol into gasoline allows gasoline to evaporate more easily and increases the difficulty of controlling emissions.[58]

The use of ethanol, particularly in low-percentage blends, can significantly increase emissions of smog-forming pollutants from vehicles because the presence of ethanol increases evaporative emissions.[59] U.S. EPA estimates that expanding the use of low percentage blends of ethanol could cause an increase in VOC emissions by 4 to 5 percent in some areas. Emissions of nitrogen oxides could increase by 6 to 7 percent.[60] Thus, fuels with high percentages of ethanol, such as E85, are preferable to low blends.

Evidence about the air pollution impacts of higher blends of ethanol is less clear. A study by Mark Jacobson at Stanford has suggested that widespread use of E85 may lead to an increase in ozone-related deaths in some areas with a specific mix of air pollutants.[61] However, the finding of increased smog pollution contradicts studies by the U.S. Environmental Protection Agency, the U.S. Department of Energy, the National Renewable Energy Laboratory and other researchers that conclude that powering vehicles with E85 leads to less smog.[62] In addition, the scenario postulated in the Stanford study is improbable. It assumes the complete replacement of gasoline by E85 in 2020, something that could not be accomplished without a near-complete replacement of the vehicle fleet. Yet, the study assumes limited turnover in the vehicle fleet when incorporating the impact of vehicle emission control systems: limited fleet turnover reduces the percentage of vehicles with strong emission control systems.

Furthermore, Jacobson assumes that manufacturers would not change their emission control systems on vehicles they know would be burning ethanol. Using ethanol in an engine configured to consume gasoline results in nitrogen oxide (NOx) emissions that are lower than required by law. In some circumstances, reduced NOx emissions can result in greater ozone pollution, but that is not consistently the case, as Jacobson assumes. Furthermore, in reality, manufacturers will produce cars that meet minimum pollution standards and will respond to a cleaner fuel by producing vehicles with weaker pollution control systems.

## Water Pollution

Increased agricultural production or greater use of fertilizers to boost production on existing land may increase runoff and leaching of nitrogen and phosphorus into surface and ground water. These contaminants can cause eutrophication, harm aquatic life, and taint drinking water supplies.[63]

Refining can also lead to water pollution. Refineries need to treat wastewater before

*Switchgrass grown on marginal cropland has a smaller impact on global land use patterns. Credit: NRCS*

releasing it to limit levels of organic material that can harm waterways.

Ethanol refineries can be large users of water, but proper wastewater treatment can allow the refinery to recycle its water. In addition, wastewater treatment allows the refinery to capture methane and use it for energy.

## Deforestation and Land Use Impacts

Planting crops to produce biofuels, especially on a wide scale, will spread the problems of modern agriculture and lead to the loss of forests and natural areas. Even collecting crop and forestry wastes can be problematic.

Cultivating land to grow corn for ethanol production creates the same environmental problems as other forms of industrialized agriculture, including pesticide runoff, soil erosion, nutrient enrichment of waterways, and use of genetically engineered organisms. These problems are more severe with corn than with switchgrass and other energy crops, which require less fertilizer and pesticide.

Converting currently unfarmed areas to production of corn or an energy crop for ethanol can cause additional environmental problems. First, the change in land use and loss of ecosystems that absorb carbon can increase global warming pollution so much that it negates any benefit from producing more ethanol.[64] Second, a strong push for more energy crops can lead to the destruction of valuable and sensitive natural areas. Diverse habitats may be replaced by monoculture. Biodiversity can be maintained by requirements for preserves, or limits on what land can be farmed.

The land use impacts of growing feedstocks for ethanol extend beyond the boundaries of a cornfield that will supply an ethanol refinery. As discussed earlier, higher demand and prices for corn will induce not only one farmer to turn a wheat field into a corn field, but prompt another farmer to respond by converting a pasture into a wheat field, thus creating a chain of impacts.

Collecting agricultural and forestry wastes as cellulosic material for making ethanol can reduce the need for new farmland for biofuels production. However, over-aggressive harvesting can result in the loss of soil nutrients, less moisture retention and greater erosion in the case of crop wastes, and could harm forest health in the case of forestry wastes.[65]

### Competition with Food Production

A final concern about growing corn and other plants to make ethanol is that it displaces the cultivation of food crops. In the short term, the too-fast development of corn ethanol is raising the price of corn and other food, both here and abroad. The U.S. currently provides 65 percent of international corn exports.[66] Countries that rely upon corn imports from the United States to feed their populations are finding it more difficult and expensive to do so. For example, corn prices have already increased, soaring 80 percent in a year, and prompting outrage and protests in Mexico over the cost of tortillas.[67]

In the long term, higher prices for corn will encourage farmers to begin cultivating more acres of land, potentially bringing down food prices but also increasing emissions of global warming pollutants from land use.

### Oil Replacement

Using corn ethanol can reduce America's dependence on petroleum. Some studies suggest that reductions in petroleum consumption from each energy-equivalent unit of ethanol can be as high as 95 percent.[68]

Significant amounts of fossil fuels such as coal and natural gas are used to produce ethanol. As a result, ethanol reduces fossil fuel consumption by only a modest amount. Current methods of producing corn ethanol reduce total fossil energy by 5 to 26 percent versus gasoline, according to one estimate.[69] This conclusion is disputed by some researchers.[70]

Thus, corn ethanol can help reduce our dependence on imported oil and vulnerability to its price variations.

### Cost

Because a gallon of ethanol contains less energy than a gallon of gasoline, the price of the two fuels must be compared on an energy-equivalent basis. In October 2007, when a gallon of gasoline cost $2.76, an equivalent amount of energy in the form of E85 cost $3.39.[71]

Ethanol receives multiple subsidies but such subsidies likely are not necessary to ensure profitability of ethanol production. Currently, fuel blenders receive a federal subsidy of $0.51 per gallon of ethanol they blend with gasoline, which encourages ethanol production.[72] Total federal and state subsidies for ethanol reach $5.1 billion to $6.8 billion per year, but observers believe that ethanol production in 2006 and 2007 would have been profitable for producers even without subsidies.[73]

To increase the use of ethanol, gas stations may need to construct more tanks dedicated to E85 at an estimated cost of $100,000 to $150,000 each. Converting an existing gas tank to dispense E85 costs $10,000.[74] In addition, automakers would need to increase their production of "flex-fuel" vehicles capable of running on both E85 and gasoline. The incremental cost of a flex-fuel vehicle is low: manufacturers often sell flex-fuel vehicles at no additional cost over a gasoline-only version.[75]

## Biodiesel

Though both ethanol and biodiesel are produced from crops and natural products, the process to create each is different. Biodiesel often is derived from oil crops such as soybeans and canola, but also can be made from used vegetable oil and animal fats. The fat is mixed with an alcohol, triggering a chemical reaction that produces biodiesel. In addition, diesel substitutes can be produced from non-fatty biomass using the Fischer-Tropsch process, in which the biomass is converted to a gas and then to a liquid.

## Global Warming Impact

Life-cycle global warming pollution emissions from biodiesel can be as much as 98 percent less than conventional diesel, if the diesel is made from waste cooking oil. Biodiesel from soybeans, the most common feedstock for biodiesel, is at least 50 percent more polluting than conventional diesel.[76] Many of the factors that influence global warming emissions from ethanol matter in determining emissions from biodiesel, including what feedstock is used and how it is produced, what secondary land use changes it incurs, how far it is transported, what fuel powers the refinery, and the efficiency of the vehicle in which the biodiesel is consumed.

### Feedstock Production

Feedstock for making biodiesel must be obtained by growing and harvesting a crop or by collecting waste animal or vegetable fats. As with feedstocks for ethanol, land use practices, pesticide and fertilizer use, and choice of crop affect the life-cycle carbon content of biodiesel.

Multiple studies have found that land use changes triggered by producing feedstock for biodiesel can cause the fuel to have greater life-cycle emissions than petroleum diesel.

Canola and soybeans, the two primary crops that can be processed for biodiesel, do not yield as much energy per acre as corn

*Canola can be processed to produce biodiesel, but its emissions may be higher than conventional diesel. Credit: stock.xchng* or cellulosic material does for ethanol.[77] That makes cultivation and harvesting of oil crops more energy intensive and it increases the potential for conflicts between growing crops for food versus biofuels. It also increases the scale of worldwide land use changes that occur in response to the diversion of the soybean crop to fuel production instead of food.

Researchers recently evaluated emissions from secondary land use changes triggered by increased biodiesel demand in the U.S. Under a variety of scenarios—including one of decreased demand for soy oil, improved yield in other countries, and conservative assumptions about emissions from newly cultivated land—biodiesel resulted in greater life-cycle emissions than petroleum diesel.[78] An earlier study found that biodiesel derived from soy causes a net increase in global warming emissions due to large nitrous oxide and carbon dioxide emissions from agricultural practices.[79]

Using waste cooking oil in biodiesel does not create any global warming pollution from feedstock production. Waste from ethanol production can also be used to produce biodiesel.

**Transportation to the Refinery**

Most analysts assume that biodiesel refineries will be located close to feedstock sources, meaning that feedstock will not have to be transported very far. As mentioned in the ethanol section, moving the feedstock by train instead of truck will result in lower emissions from this step.

**Refining**

As with ethanol, refining biodiesel can produce different amounts of global warming pollution depending on whether coal, natural gas or biomass provides heat and power for the refining process.

Biodiesel can be produced through several processes that vary in energy intensity and thus global warming emissions. For example, soy biodiesel provides a greater global warming pollution reduction than does corn ethanol because the refining process is less energy intensive.[80]

The creation and use of refining co-products also influences the carbon-intensity of refining. Soybeans and canola produce a protein co-product that can be used as animal feed.[81] Feeding livestock this biodiesel co-product instead of protein meal that has been manufactured explicitly as feed reduces the life-cycle emissions from these sources of biodiesel.

**Transportation to Market**

As with ethanol, inputs for producing biodiesel must be transported from the place of feedstock production to the refinery, and then from the refinery to market. One analysis that compares biodiesel from five different feedstocks finds that all biodiesel feedstocks produce greater emissions than petroleum diesel during feedstock and fuel transportation.[82] The higher emissions from transportation to market result from an assumption that refineries will be located close to feedstocks rather than consumers.

**End Use**

Biodiesel (particularly in low percentage blends) can be used in any diesel vehicle. Some older vehicles may need to have rubber components of the fuel line replaced because the biodiesel can corrode them, but these vehicles are generally capable of operating on biodiesel. Biodiesel contains 11 percent less energy per gallon than conventional diesel, so vehicles cannot travel as far on a tank of biodiesel.[83]

In summary, biodiesel may provide significant global warming pollution savings compared to conventional diesel, but these benefits are strongly dependent on how the biodiesel is produced. Life-cycle emissions from soybean biodiesel are likely 52 to 158 percent higher than petroleum diesel.[84] Even accounting for the fact that biodiesel is less energy dense, biodiesel from waste cooking oil releases 98 percent less global warming pollution, but limited supplies of waste oil mean that not much waste oil-based biodiesel can be produced.[85] In the long run, should cellulosic ethanol technology move forward, wastes from that process could be used to produce larger quantities of diesel substitute.

### Air Pollution

Biodiesel, more clearly than ethanol, reduces most types of air pollution. Biodiesel refining results in lower emissions of some pollutants compared to diesel. Use of biodiesel—from low-level blends to pure biodiesel—results in lower vehicle emissions of VOCs, carbon monoxide, particulate matter ($PM_{10}$) and sulfur dioxide.[86]

The impact of biodiesel on emissions of nitrogen oxide is less certain. A recent National Renewable Energy Laboratory (NREL) study found no increase in NOx emissions from 20 percent biodiesel fuel blend, contradicting earlier studies from EPA.[87] However, the EPA study involved older vehicles with less effective emission control systems and thus the NREL study may be more representative of current and future biodiesel emissions.[88]

### Water Pollution

Crops grown for biodiesel have many of the water pollution problems of crops grown for ethanol. In addition, because biodiesel crops yield less energy per acre farmed, producing a gallon of biodiesel requires more cultivation and thus potentially more water pollution.

### Deforestation and Land Use Impacts

Because canola and soybeans produce less energy per acre farmed, a dramatic increase in demand for oil crop-based biodiesel would require a very large increase in the acreage dedicated to fuel production. For example, even if the entire soybean crop in the U.S. were converted to biodiesel, it would replace only 6 percent of petroleum diesel used in the U.S.[89]

Thus, significantly increasing biodiesel production will conflict with other land uses, such as farming for food or maintaining forestland. Already, European demand for biodiesel has spurred the destruction of sensitive ecosystems in other parts of the world to make room for planting oil palm plantations for fuel. And as discussed above, these changes provoke huge increases in global warming pollution from biodiesel.

### Competition with Food Production

Oil crops like soybeans produce far less energy per acre than cellulosic sources or corn.[90] Thus, dramatic expansion of biodiesel production could cause greater competition with food production than growing crops for ethanol does.

### Oil Replacement

Biodiesel's potential to replace large amounts of current petroleum consumption is limited.[91] The low energy yield of biodiesel crops means that there simply is not enough land on which to grow crops to replace much petroleum diesel. Only a small amount of biodiesel can be made from waste cooking oil because feedstock supplies are so limited.

### Cost

Biodiesel is slightly more expensive than petroleum diesel. In October 2007, when a gallon of diesel cost $3.11, an energy-equivalent amount of B20 biodiesel cost $3.14. Pure biodiesel cost $3.72.[92]

## Electricity

Though electricity may not be the first vehicle fuel that comes to mind, it can be a low-carbon source of energy for transportation. Hybrid-electric vehicles, such as the Toyota Prius, are powered by both gasoline and electricity. The vehicle's battery is charged by the gasoline engine and through the capture of energy lost during deceleration. Plug-in hybrid vehicles have a larger battery that can be charged using power from the electricity grid, as well as by a regular gasoline engine as a backup. Full battery-electric vehicles operate solely on electricity.

## Global Warming Impacts

Numerous studies have concluded that electric-powered vehicles produce lower global warming emissions than conventional gasoline-powered cars and trucks. For example, a plug-in hybrid electric vehicle with a 20-mile all-electric range is 62 percent less polluting than a gasoline vehicle, assuming that the vehicle is recharged from California's relatively low-carbon electric grid.[93]

Life-cycle analysis of the global warming emissions of electric vehicles typically includes an evaluation of how electricity is generated and the efficiency with which it is used in vehicles, but excludes mining and transportation of the fuel before it reaches the power plant. Adding these steps to life-cycle analysis of electricity would help ensure that electricity is evaluated on equal terms with other fuels.

### Power Generation

Emissions from plug-in and full electric vehicles are heavily influenced by what fuel is used to generate electricity and how efficiently that electricity is generated.

Electricity in the U.S. is most frequently generated at coal-fired power plants, which have very high global warming emissions. Coal-fired power plants release more than 2,000 pounds of carbon dioxide for every megawatt-hour of electricity generated. In contrast, the average natural gas power plant releases 1,100 pounds of carbon dioxide.[94] Electricity generated from wind or solar power releases no global warming emissions.

Charging electric vehicles with power from zero-emission renewable energy sources would result in vehicles with extremely low emissions. Unfortunately, the electricity grid does not allow picking and choosing between power sources on a day-to-day basis. To reduce emissions from electricity, the overall mix of generating facilities must be changed to retire dirty coal-fired power plants and replace them with cleaner natural gas or renewable generating capacity.

Developing renewable energy sources such as wind and solar power and reducing coal-fired generating capacity will make vehicles that rely on electricity even cleaner. Ultimately, as the amount of renewable generating capacity on the electric grid increases, a rising portion of the vehicle fuel will come from renewable energy.

### Transportation to Market

As electricity is sent through power lines, thermal losses and other inefficiencies mean that a portion of the power never reaches consumers. To provide a kilowatt-hour of electricity to a customer requires generating more than a kilowatt-hour at the power plant. This inefficiency raises emissions from coal or natural gas-fired power plants.

Power that is generated close to consumers will incur almost no transmission loss and will therefore have lower emissions. And electricity generated from solar panels installed on the roof of a home will have no emissions and no transmission losses.

### End Use

A major contributor to the reduced global warming emissions of electric vehicles is the inherent efficiency of an electric motor compared to an internal combustion engine. An electric drivetrain is five times more efficient than a gasoline internal-combustion engine.[95] This efficiency enables an electric-powered vehicle—even one using electricity generated in a coal-fired power plant—to have relatively low global warming emissions.

Drivers of electric vehicles who live in free-standing homes should be able to recharge vehicles at home. To facilitate re-charging at large apartment complexes or at workplaces, additional infrastructure may need to be built.

The time of day at which a plug-in hybrid or battery-electric vehicle is recharged will influence emissions (and cost, discussed later). During the day, power companies operate all their power plants to meet high demand; at night, the most expensive plants—typically natural gas plants—are turned off and just baseload facilities—currently coal or nuclear power plants—operate. This can result in higher night-time emissions. However, in coming years, as more wind generation capacity is installed, wind energy may provide a greater percentage of electricity generated at night. Additionally, because wind turbines can generate more power at night than during the day, charging vehicles with wind power overnight may become a convenient way of storing clean energy to feed back into the electric grid during the day.

In summary, even an electric vehicle that draws power from the national electricity grid, which includes many carbon-intensive energy sources, produces less global warming pollution than a gasoline vehicle. Research by the Argonne National Laboratory concludes that plug-in hybrids are 36 percent less polluting.[96] According to this same study, a plug-in hybrid recharged from California's grid would be 44 percent cleaner than gasoline.

## Air Pollution

Should the widespread use of electric vehicles result in increased consumption of coal or natural gas, an increase in air pollution could result (although federal and state air quality regulations limit emissions of some pollutants from power plants). Coal-fired power plants release mercury, nitrogen oxides and sulfur dioxide. Mercury is a neurotoxin that delays development in children. Nitrogen oxides contribute to smog, which can lead to asthma, bronchitis, emphysema and other respiratory and cardiovascular problems. Sulfur dioxide is a component of fine particulate matter pollution, which can cause asthma, cancer and premature death. Modern coal-fired power plants control much of this pollution, but older plants have less effective pollution controls. Natural gas power plants are cleaner than coal-fired plants, but have higher emissions than renewable sources of energy.

## Water Pollution

Waste material from a type of coal mining known as mountain-top removal is typically piled in valleys, blocking streams and leaching into water supplies. Other forms of coal mining also produce rock and dirt that is heaped in piles. When these piles are exposed to rain, they release toxins into streams and groundwater.

Drilling for natural gas creates sediment and toxic pollution, as well as large quantities of saline water that can degrade the quality of waterways or groundwater resources if improperly managed.[97] Other forms of electricity generation—including nuclear power and large hydroelectric dams—can also pollute or otherwise degrade water resources.

Fossil fuel power plants (and some central solar facilities) typically use water for cooling. If that water is released back into the river or lake from which it was taken, the higher temperature can cause fish kills and alter the ecosystem of the waterbody. If water is not released and is evaporated instead, it is no longer available to other users.

## Land Use Impacts

Coal mining destroys habitat and pollutes land so that future uses are limited.

In mountain-top removal coal mining, for example, entire hillsides are scraped away to expose the coal beneath. Material with concentrations of coal too low to be burned is discarded in giant waste heaps. Even when a mountain-top mining site is "reclaimed," the land remains tainted and the soil is inadequate to support the same forest as existed before mining.

Natural gas drilling offshore disturbs marine wildlife. Onshore, drilling infrastructure and pipelines create industrial sites within otherwise natural areas and fragment habitat. Pipelines for transporting natural gas extend hundreds or thousands of miles, cutting through ecosystems and fragmenting habitats.

*A single coal mine can destroy hundreds of acres of land. Credit: stock.xchng*

## Oil Replacement

Electricity can reduce oil consumption. Hybrid-electric vehicles do require gasoline but not as much as vehicles powered by a standard internal combustion engine. The Toyota Prius, for example, is EPA-rated to travel 46 miles per gallon of gasoline, compared to 27.5 miles per gallon for the average car. Plug-in hybrids require even less gasoline.

If electric vehicles are recharged at night, the U.S. has sufficient generating capacity to supply energy to many vehicles. Daytime electricity supplies are more limited and for that reason, night-time recharging could be preferable.

## Cost

Retail electricity prices average 8.9 cents per kilowatt-hour, but vary around the country. Charging an electric vehicle or plug-in electric vehicle and operating it in all-electric mode would cost consumers 3 cents per mile, assuming a vehicle efficiency of 3 miles per kilowatt-hour.[98] This is a lower cost per mile than a gasoline or hybrid-electric vehicle (more than 6 cents per mile if gasoline costs $3 per gallon).

It costs less to charge a vehicle at night than during the day because cheaper (but higher emission) power plants predominate at night. This price difference will matter to individual consumers only if they have a time-of-day pricing plan from their electric utility. However, all consumers will have to pay higher prices for electricity if vehicles are recharged during the day, driving up peak demand and requiring construction of more power plants.

Widespread use of electric vehicles offers new flexibility for the operation of the electricity system. Electric vehicles could be charged at night, when generating capacity is abundant and prices are lower. During the day, when vehicles are parked, the electricity stored in their batteries could be fed back into the power grid, thereby reducing the need for other sources of electricity to meet peak demand. Such an approach could reduce electricity costs by limiting the need to build new plants for times of high demand.

# Natural Gas

Vehicles operating on natural gas are in widespread use throughout the U.S. in government and utility company vehicle fleets. Expanding natural gas vehicle use could reduce global warming pollution.

## Global Warming Impact

Compressed natural gas vehicles produce as much as 26 percent less global warming pollution over their life-cycle than gasoline powered-vehicles.[99] Natural gas drilling and processing, transport to consumers, compression, and end use all contribute to emissions.

### Feedstock Production

Natural gas must be drilled and processed before it is fed into a pipeline. This production releases global warming pollution.

### Transportation to Market

Natural gas is transported to consumers via pipeline, an efficient way to move fuel. However, a typical mile of natural gas pipeline leaks 1,360 pounds of methane, a powerful global warming pollutant, each year.[100]

### End Use

The only commercially available light-duty vehicle that operates on natural gas is the Honda Civic GX, which is moderately efficient.[101] By one estimate, the Honda Civic GX averages the equivalent of 28 miles per gallon.[102] Natural gas has also come to be a common fuel in transit bus fleets.

Fueling a natural gas-powered vehicle requires compressing the natural gas so that more of it can be carried in the vehicle's tank. Most natural gas compressors in the U.S. are powered by electricity. Electric-powered compressors are marginally more efficient than those powered by natural gas.[103]

Finally, natural gas has lower emissions than gasoline. Analyses of natural gas's pollution using EPA's emission model calculate that it produces 18 to 26 percent less global warming pollution than gasoline.[104] Another, more conservative analysis estimates savings of just 5 percent.[105]

In the short term, natural gas may be a useful fuel for transitioning to lower emission fuels—particularly for vehicle fleets that are refueled centrally, such as transit buses. The California Energy Commission has identified natural gas as one of the fuels the state should use in transitioning to lower-emission transportation fuels, especially in the early years as other fuels are still being developed.[106]

## Air Pollution

In terms of toxic and smog-forming pollutants, natural gas is a much cleaner fuel than gasoline. Natural gas vehicles release 56 percent less nitrogen oxide, 41 percent less carbon monoxide, and 84 percent less sulfur dioxide, but 68 percent more particulate matter.[107]

Fueling stations that rely upon electric compressors will not produce any on-site emissions, an important consideration for urban locations, though pollution will be released at the power plant. Natural gas compressors, in contrast, will release nitrogen oxides and other pollutants.

## Water Pollution

Natural gas drilling releases sediment, toxics and saline water that can pollute groundwater and nearby waterways.

## Land Use Impacts

As discussed with electricity, drilling for natural gas and building pipelines to transport that gas disturb thousands of acres of habitat. (See p. 26.)

## Oil Replacement

Natural gas has limited capacity for replacing oil in the long run. The U.S. has small reserves of natural gas: 2006 levels of production can be sustained for only 11.3

years, given current knowledge of natural gas reserves.[108] Moreover, demand for natural gas in other sectors of the economy is on the rise, especially in the electricity sector, where natural gas is seen as a cleaner alternative to coal.

Internationally, natural gas supplies are greater, but importing natural gas is problematic on several counts. Natural gas has very low energy density that makes transport by tankers inefficient unless the gas is cooled to -256 degrees Fahrenheit, when it becomes a liquid. Once the gas is delivered to its destination, it must be warmed to return it to a gaseous state that can be fed into a pipeline. (This additional transportation and processing required for imported natural gas would raise life-cycle emissions of natural gas-powered vehicles.) Locating liquefied natural gas terminals near crowded coastal cities is potentially dangerous and building them in remote locations destroys delicate coastal ecosystems. All options for importing natural gas are expensive. Furthermore, replacing imports of petroleum with imports of natural gas does nothing to enhance our energy independence.

## Cost

Compressed natural gas is significantly cheaper than an energy-equivalent amount of gasoline. Whereas a gallon of gas cost $2.76 in October 2007, an energy equivalent amount of compressed natural gas cost $1.77.[109]

However, building new refueling infrastructure to facilitate wider use of natural gas is costly. A residential refueling unit that compresses natural gas from a household natural gas line costs more than $4,000.[110] Refueling is relatively slow—adding enough fuel to drive 50 miles takes four hours.[111] New commercial refueling stations will not be cost-competitive with gasoline and diesel stations until natural gas achieves a 20 percent market share.[112]

# Hydrogen

## Global Warming Impact

Hydrogen's impact on global warming depends entirely on how the hydrogen fuel is produced. Hydrogen is not a primary energy source—it exists on its own virtually nowhere in nature. Instead, hydrogen must be extracted from other compounds, either water (through a process called electrolysis) or fossil fuels. If hydrogen is generated from electrolysis powered by renewable energy, it can reduce global warming pollution per mile driven by more than 90 percent.[113] If, however, hydrogen is produced directly from fossil fuels such as natural gas, or created through electrolysis using electricity generated from coal, it produces far less reduction in global warming pollution.

### Feedstock Production

Hydrogen can be produced from different sources, including natural gas, biomass, and water. All production methods are energy-intensive. Therefore, the choice of feedstock and how it is processed are important determinants of life-cycle global warming pollution from hydrogen.

The lowest-emission option is to use renewable energy to create hydrogen from water by electrolysis: exposing water to an electric current splits it into its constituent parts—hydrogen and oxygen. Electrolysis requires a large amount of electricity. Electricity generated by wind or solar energy results in hydrogen with essentially no global warming emissions, but electricity from coal or natural gas is much dirtier. In some parts of the country, scarce water supplies may limit the potential for producing hydrogen from water.

The next-lowest emissions are from hydrogen created (or "reformed") from natural gas or biomass. Reformation involves exposing the fuels to high-temperature steam in the presence of a catalyst.

The result of the process is hydrogen and carbon dioxide. Gasification involves using a super-heated reactor to turn biomass or other fuels into a gas, which is then exposed to steam and oxygen to create hydrogen, carbon monoxide and carbon dioxide. (This method can also be used to create hydrogen from coal.)

Using natural gas as the power source to create hydrogen, according to a study by the National Academy of Sciences, would cut greenhouse gas emissions by 30 to 50 percent compared to hybrid-electric vehicles running on gasoline.[114] Hydrogen generated using biomass—such as plants, plant wastes or animal wastes—can reduce global warming emissions by 60 to 100 percent.[115] However, were coal to power the hydrogen production process, emissions from a hydrogen-powered vehicle would be equal to or greater than those from a hybrid-electric vehicle.[116]

**Transportation to Market**

Hydrogen can be distributed to consumers in two ways. Centralized distribution would operate much like the current gasoline distribution system. Hydrogen would be processed at large-scale facilities and then be distributed to filling stations by pipelines and tankers. However, as with ethanol, hydrogen's low energy density means that a tanker truck hauling hydrogen will expend essentially the same amount of energy and produce the same emissions as if it were hauling gasoline.

A decentralized distribution approach means that hydrogen would be produced at filling stations from natural gas or water. Some of the basic infrastructure needed for this—pipelines for natural gas and power lines for electricity—already exists. The drawback is that such small-scale production of hydrogen could be less efficient and more costly.

**End Use**

Hydrogen can be used in vehicles with fuel cells or internal combustion engines. Fuel cell vehicles use hydrogen to generate electricity, which powers an electric motor, allowing fuel cell vehicles to benefit from the drivetrain efficiency of electric motors. Many estimates of fuel cells assume a high level of efficiency for hydrogen vehicles. The National Academy of Science, for example, assumes that hydrogen fuel cell vehicles are as efficient as a conventional vehicle that can travel 65 miles per gallon of gasoline, or more than twice as efficient than the average car.[117] In contrast, hydrogen consumed in an internal combustion engine is only 23 percent more efficient than a gasoline vehicle.[118]

In summary, the global warming impact of hydrogen ranges from almost zero to greater than a conventional gasoline vehicle.

## Air and Water Pollution

As with electricity, many of hydrogen's air and water pollution impacts are contingent upon the fuel used to create hydrogen. Tailpipe emissions of toxic compounds would be minimal and per-mile emissions of nitrogen oxides would drop 47 percent compared to conventional vehicles.[119]

## Land Use Impacts

Mining fuel to create electricity for hydrogen production will have the same impacts as discussed in the electricity section above. (See p. 26.) Hydrogen may also have other land use impacts if new pipelines are constructed to transport hydrogen from centralized production facilities or if new fueling stations are constructed to distribute the fuel.

## Oil Replacement

Shifting large numbers of vehicles from gasoline to hydrogen certainly would reduce our dependence on foreign oil. However, greater hydrogen demand could cause natural gas consumption to increase, potentially requiring greater imports of natural gas. Assuming that hydrogen is produced from natural gas using current technologies, a study by the National Academy of Sciences suggests that converting half of the nation's vehicles to operate on hydrogen would increase natural gas consumption by 16 to 22 percent compared to 2002 levels.[120] Domestic reserves of natural gas are limited, so meeting this increased demand could require importing more natural gas.

### Cost

Hydrogen is an expensive fuel to create and to use. Creating a generation and distribution system, whether centralized or decentralized, would require development of new infrastructure. A decentralized filling station that could serve 854 cars per week, for example, could cost $1.85 million to build.[121] While a centralized distribution system is more cost effective on a per-vehicle basis, cost-effectiveness relies upon widespread penetration of hydrogen vehicles into the marketplace. Decades will pass before such economies of scale can be achieved.

Consumers will pay an additional $6,000 to $11,000 for a hydrogen fuel cell vehicle compared to a gasoline vehicle in 2020, even if vehicle production reaches 100,000 vehicles annually.[122] On an energy basis, consumers likely will pay more for hydrogen than gasoline in 2020, though the greater efficiency of hydrogen fuel cell vehicles will mitigate this expense. The estimate assumes that 10 percent of fuel use is hydrogen.[123]

To achieve any of these price levels, industrial and governmental financing for research and development will need to continue at approximately $600 million to $1 billion annually.[124]

## Coal-to-Liquid Fuel

Coal can be processed to create a liquid that serves as a diesel substitute. While coal-to-liquids has received much attention recently as a technology that can help reduce U.S. imports of oil, it creates so much global warming pollution that it is an unacceptable solution to our energy problems.

### Global Warming Impact

Liquid produced from coal creates more than twice the global warming pollution of gasoline and nearly twice the emissions of diesel on a life-cycle basis.[125] The fuel starts with a high-carbon energy source and requires heavy processing.

#### Feedstock Production

Coal-to-liquids production starts with the mining of coal, a heavy industrial process that requires petroleum-powered equipment that releases global warming pollution. Perhaps more importantly, coal mining can release methane, which is frequently trapped in coal beds. Methane is a greenhouse gas 16 times more powerful than carbon dioxide. When coal beds are opened for mining, the methane is released into the atmosphere.

#### Transportation to the Refinery

Coal is typically transported by rail because rail lines have been built to serve mines. Coal-to-liquids processing facilities may be constructed near mines to reduce the distance coal must be transported.[126]

#### Refining

Coal-to-liquids fuel is not yet commercially produced in the U.S. but the federal Energy Information Administration (EIA) expects that production could begin within the next few years. At the refinery, coal will first be turned into a gas and then converted into a liquid using the Fisher-Tropsch process.[127] According to an estimate by EIA, just 49 percent of the energy in the original coal will remain in the final, liquid product. Twenty percent of the energy in the coal will be consumed to manufacture the liquid. If the facility has co-generation capacity and can generate electricity, then 30 percent of the energy will be sold into the power grid. However, if the plant is located near a coal mine, it likely will be a great distance from consumers who want to buy electricity.

**Transportation to Market**

The refined fuel could be moved to market via rail, truck or perhaps pipeline. Coal-to-liquids refineries built near coal mines will not necessarily be close to markets for fuel, so the product may have to be shipped a substantial distance.

**End Use**

Liquid fuel produced from coal can be consumed in place of gasoline or diesel in a conventional vehicle. As with ethanol and biodiesel, the overall efficiency of the vehicle and the inefficiencies of internal combustion engines will influence tailpipe emissions from end use.

In summary, extensive processing of a high-carbon fuel means that coal-to-liquids fuel has approximately twice the life-cycle global warming pollution of conventional gasoline.[128] Even if a coal-to-liquids facility were able to capture and sequester carbon released during the coal-to-liquids process,

## New Petroleum-Based Fuels Have High Emissions

Oil shale and tar sands have drawn the interest of energy companies for decades as possible new sources of oil. As oil prices rise and as the U.S. seeks to increase its domestic production of oil, oil shale and tar sands have again entered the conversation. However, the fuels have high life-cycle global warming emissions, their production creates extensive environmental damage, and they have little potential to displace much imported oil.

### Oil Shale

Oil shale refers to sedimentary rock with a solid petroleum substance trapped between the layers. If the rock is heated, the oil becomes a liquid and is released, at which point it can be processed as a synthetic crude oil.

Transportation fuels produced from oil shale have significantly higher global warming pollution emissions than conventional gasoline or diesel.[139] Oil shale releases its oil when it is heated to 700 to 900°F. Producing that much heat requires a tremendous amount of energy: under one method of production, all the electricity from a medium-sized power plant would be required to produce fuel that would replace just 1 percent of daily U.S. gasoline consumption.[140] A coal or natural gas power plant of this size would release millions of pounds of carbon dioxide. Thus, total life-cycle emissions of oil shale are extremely high.

Processing oil shale causes other environmental damage. Producing a single barrel of oil from shale requires as much as 5 barrels of water, a severe problem given that oil shale deposits in the U.S. are concentrated in the arid Mountain West.[141] Whether oil shale is processed on site or is mined and processed off-site, the low energy density of oil shale means that large areas have to be disturbed. To extract the liquid fuel itself still produces life-cycle emissions 4 to 8 percent greater than those of gasoline.[129]

## Air Pollution

Coal-to-liquids processing facilities will produce air pollution. Operators of a proposed refinery in Gilberton, Pennsylvania, project that it will release 29 tons per year of sulfur dioxide, 70 tons per year of nitrogen oxides, 23 tons per year of particulate matter, and 54 tons per year of carbon monoxide.[130] Sulfur dioxide contributes to acid rain, nitrogen oxides are a precursor to smog and particulate matter, which can cause lung damage and worsen heart disease, and carbon monoxide can be toxic.

## Water Pollution

As discussed regarding the use of electricity as a transportation fuel, coal mining creates significant water pollution.

Furthermore, coal-to-liquids processing facilities consume large quantities of water. Producing one gallon of fuel requires 2.5 to 5 gallons of water for processing, resulting in very large total withdrawals.[131] The proposed coal-to-liquids facility in Gilberton, Pennsylvania, has received a permit to withdraw up to 7 million gallons per day.[132]

just one barrel of fuel, 1.2 to 1.5 tons of oil shale must be crushed and processed, which increases the volume of rock by as much as 25 percent.[142]

Oil shale has limited potential to displace conventional oil. Though oil shale deposits in the U.S. contain several times more oil than exists in Saudi Arabia, mining it would entail tremendous environmental destruction from increased global warming pollution, use of all available water in the region, and destruction of thousands of acres of habitat.

## Tar Sands

Tar sands consist of clay, sand, water and extremely viscous oil. With strip mining and extensive processing at high heat, the oil can be separated from tar sands for fuel.

As with oil shale, tar sands must be heated to turn the oil that they contain into a liquid, a process that results in high global warming emissions. Canada's tar sands industry estimates that producing a barrel of oil from tar sands consumes the same amount of natural gas that could heat a home for one to four days.[143] Overall, increasing production of oil from tar sands is the biggest factor driving up Canada's emissions of global warming pollution.[144]

Extracting oil from tar sands tears up land and consumes high volumes of water. Deposits of tar sands near the surface are accessed with vast surface mines. Two tons of sand produce just one barrel of oil, so any large-scale production requires moving huge amounts of soil.[145] Mining and processing tar sands can consume nearly six gallons of water for every gallon of oil produced.[146] As with oil shale, tar sands in the U.S. are concentrated in areas with limited water resources. Tar sand mining in Canada has caused widespread environmental damage.[147]

U.S. reserves of tar sands are equal to 12 to 19 billion barrels of oil.[148] Recovering even a small percentage of this will raise global warming pollution and destroy natural resources near the mining site.

## Land Use Impacts

Coal-mining irreparably destroys huge swaths of land, as discussed earlier. (See p. 26.)

## Oil Replacement

Liquid fuel made from coal technically could replace all of the imported oil that we consume today. Domestic coal reserves are great enough to produce 800 billion barrels of liquid fuel, equal to 167 years of petroleum consumption at current levels.[133] However, this would require a huge increase in coal mining. To replace just 10 percent of current transportation-related petroleum consumption, coal mining would need to increase by 25 percent from current levels, worsening the water and air pollution impacts of coal mining.[134]

## Cost

Coal-to-liquids fuel is technically feasible, but very expensive. Building a coal-to-liquids refinery can cost billions: one proposed facility in Ohio would cost $4 billion to construct.[135] Building enough refining capacity to replace 10 percent of current petroleum use would cost $70 billion, according to a study by researchers at M.I.T.[136] The researchers add a note of caution that historic projections of the costs of building synthetic fuel refineries have been "wildly optimistic," suggesting that the price tag could be far higher.

Compared to refining oil, converting coal into liquid fuel is costly. Even without carbon sequestration, refining coal into liquid costs three to four times as much as refining the same amount of oil.[137]

Because coal-to-liquids fuel is so expensive and private capital markets will not finance construction of such risky plants, a coalition of industry and labor groups has sought subsidies, federal loan guarantees and production tax credits to facilitate coal-to-liquids production, with some success.[138] In 2005, Congress agreed to provide funds for construction of coal-to-liquids plants, but has not yet allocated the funds. However, any production of coal-to-liquids is unlikely if the U.S. commits to reducing its global warming pollution and turns away from the most polluting energy sources.

# Getting the Most from Alternative Fuels

No single alternative fuel will be the solution to America's energy and global warming challenges. Indeed, the use of alternative fuels must be just one piece of a larger strategy to reduce the contribution of the American transportation system to global warming—a strategy that also includes reducing the number of miles driven in vehicles and improving vehicle energy efficiency.

Alternative fuels, however, can play an important role in addressing these challenges, if America develops a smart strategy to maximize their benefits. Such a strategy should have three components.

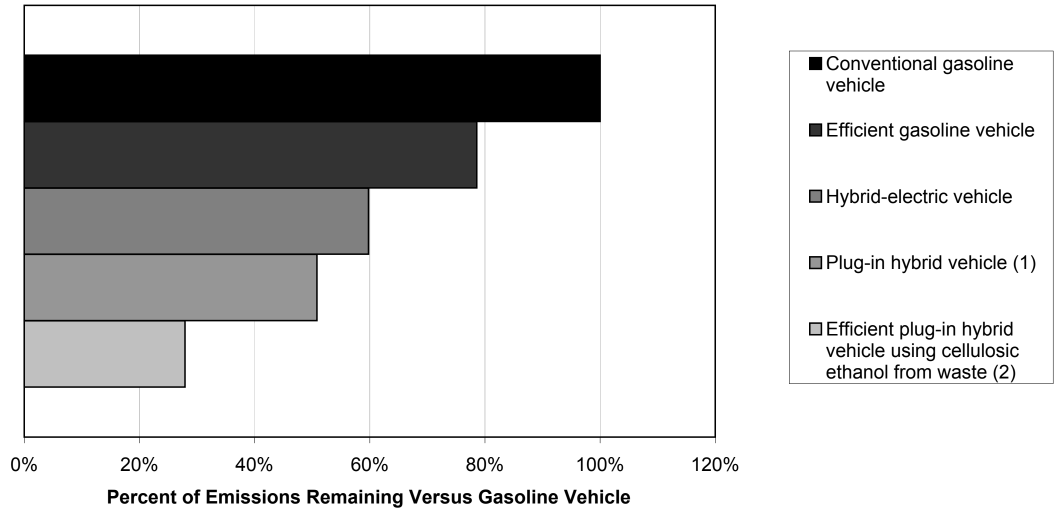
## Three Principles for Alternative Fuel Development

### Combine the most promising approaches to maximize environmental benefits.

A number of the alternative fuels discussed above have significant potential to reduce global warming pollution compared to gasoline. The greatest global warming pollution reductions, however, can be achieved by combining the cleanest technologies and fuels. Emissions from a conventional vehicle can be reduced by improving its efficiency and by powering it with a lower emission fuel. A vehicle that taps the best attributes of these options—better vehicle efficiency, use of a fuel affiliated with an efficient drivetrain, and drawing on multiple clean fuels—can achieve the greatest reductions, as show in Figure 5.

Emission reductions gained through the use of alternative fuels, therefore, should be built on top of gains made through improved energy efficiency, and not substituted for them. Public policy should provide clear incentives to combine low-emission technologies in vehicles. Unfortunately, some current policies take an "either-or" approach to fuel economy improvements and alternative fuels. For example, automakers can receive credit toward compliance with federal corporate average fuel economy standards by producing vehicles that can operate on biofuels, even though the best solution to reducing emissions is to have an efficient vehicle using a low-emission fuel.

**Figure 5. Life-cycle emissions achieved by combining the best vehicle technologies and fuels**




(1) Vehicle is recharged with electricity that has the same carbon emissions as the U.S. national average.
(2) Cellulosic ethanol produced from municipal waste. Electricity has same carbon emissions as U.S. national average.

## Develop fuels with long-term potential.

Alternative fuels vary greatly in the short-term contributions they can make toward America's energy and global warming challenges. They also vary greatly in their long-term potential.

Natural gas, for example, has the potential to reduce global warming pollution in the short term, but has little long-term potential as a transportation fuel due to limited domestic gas supplies. Hydrogen fuel has potential in the very long run, but that potential is decades away from being realized. Electricity is available today, but its potential will not be realized until automakers begin producing cars that can use electricity.

Public policy should emphasize the development of infrastructure to support promising long-term fuel options over those with only short-term potential. In some cases, that may mean developing policies that encourage the use of fuels, like electricity, with limited short-term benefits but greater long-term potential.

## Set high environmental standards and mitigate environmental and social impacts.

America will be more likely to reduce the environmental impacts of transportation fuels if we set strong environmental standards for those fuels. The first step should be to establish a low-carbon fuels standard (see next section) that encourages the development of fuels with lower life-cycle global warming emissions. Standards should also be developed and implemented to mitigate the impacts of alternative fuels on the quality of our air, water and natural ecosystems.

Significant research and study is necessary to accurately calculate life-cycle global warming emissions of various production practices of fuels and measure impacts to our air, water and natural ecosystems.

## Policies to Promote Clean Alternative Fuels

If the United States is to reduce its global warming pollution and curb its dependence on expensive and polluting fuel, it will need to develop alternative fuels. The best policy for achieving this will promote clean fuels that can be used efficiently and that have the fewest environmental impacts.

One such policy is a low-carbon fuel standard, which encourages the development of alternative fuels that have lower global warming emissions. A well-designed low-carbon fuel standard ensures that whatever alternative fuels replace gasoline will not have a negative effect on the climate in the short run and will reduce emissions over time. Furthermore, a low-carbon fuel standard can include sustainability criteria to prevent other forms of environmental harm.

### Low-Carbon Fuel Standard

A low-carbon fuel standard could be implemented in several ways, but one of the easiest routes would be to require that fuel providers—those who refine, import, or blend fuel—sell fuel with a declining carbon content. A beginning point could be a requirement that transportation fuels be 10 percent less carbon-intensive by 2020, the standard set by the state of California.

Fuel providers would be required to report the full life-cycle global warming pollution of the fuels that they sell.[149] A default emission figure for each fuel should be established by the appropriate regulatory authority, but fuel sellers should have the option of presenting data demonstrating that their fuel is less polluting than the default fuel value. Life-cycle analysis of global warming emissions should include emissions from farming practices, land use changes here and worldwide, refining, shipping and use of the fuel. The efficiency for vehicles using non-petroleum fuels in high-efficiency electric drivetrains should also be factored in. All global warming pollutants, including carbon dioxide, methane and nitrogen dioxide, from all stages of fuel production (including secondary land use impacts) should be considered.

As was evident in the discussion of the life-cycle global warming emissions of different fuels, many factors influence the environmental profile of biofuels. Accurately assessing the impact of fuels will not be simple, nor will it happen overnight. However, a low-carbon fuel standard could be implemented today, relying on estimates that encourage the production of fuels with less carbon without favoring one vehicle technology over another. As better data becomes available—thanks in part to better tracking of production pathways and fuels once a standard is in place—the standard can be revised to offer greater precision about which fuels will provide the greatest benefit.

Current uncertainties should be dealt with conservatively. For example, researchers assisting with development of California's low-carbon fuel standard acknowledge that uncertainty remains regarding emission effects of land use.[150] However, uncertainty about land use impacts should not be an excuse to assume that there is no impact from land use: giving land use impacts a value of zero could facilitate counterproductive land use practices. Instead, a low-carbon fuel policy should include a best estimate of land use impacts, with the understanding that the estimate will be revised in the future as better data become available. A low-carbon fuels policy should be flexible enough to allow the addition of new information for establishing targets and enforcing requirements.

A low-carbon fuel standard allows fuel providers flexibility in deciding how to reduce the global warming emissions from the fuel they sell. Providers could seek out supplies of cellulosic ethanol or promote the use of electricity. The amount of renewable fuel that providers sell would depend on the type of fuel.

A 10 percent reduction in global warming emissions from transportation fuels by 2020 is an ambitious, but reasonable, target. By starting the low-carbon fuel standard with a fairly low requirement and increasing the target each year, farmers, researchers and investors can anticipate future demand, developing new energy sources and technologies.

Part of the value of a low-carbon fuel standard is its ability to push the development of new technologies. Public policies that establish ambitious goals can help speed the evolution and production of cleaner technologies. California, for example, pushed vehicle technology forward with its Zero-Emission Vehicle Program, which ultimately led to the creation of battery electric vehicles that made today's hybrid-electric vehicles possible. A low-carbon fuel standard can push similar gains in vehicle fuels.

To avoid negative consequences from increasing production of low-carbon fuels, any low-carbon fuel standard should include provisions to protect air quality, public health, and the environment.

**Protect air quality and public health**

Because fuels such as ethanol blended with gasoline at certain concentrations can worsen air quality by raising emissions of toxic and smog-forming pollution and particulate matter, a fuel standard should include a requirement that low-carbon fuels at least maintain current air quality and that vehicle emission standards should not be relaxed. Low blends of biofuels, such as E10, should be discouraged. Operating a subset of vehicles on high blends such as E85 will allow a sector-wide reduction in global warming emissions without increasing air pollution.

**Protect ecologically sensitive areas**

A low-carbon fuel standard should not result in the clearing and use of ecologically sensitive areas for biofuels cultivation. Preventing adverse land use changes will be challenging because changes in crop planting and use in the U.S. can cause other changes around the world. For example, if more of the U.S. corn and soybean crop is dedicated to biofuels production rather for food here or abroad, farmers may clear additional land to increase their corn and soybean production. Inclusion of an accurate assessment of the emission effects of changing land use practices will discourage some land conversions domestically, but monitoring international impacts will be more difficult. Researchers helping California develop its low-carbon fuel standard recommend further research and coordination with Europe, which is struggling to address the same challenge.

## Complementary Policies

Though a low-carbon fuel standard will provide the biggest push for reducing the global warming pollution from transportation fuels, additional policies can make the transition to lower-emission fuels easier.

**Encourage the best ethanol production methods**

The incentives for ethanol should reflect the environmental impact of its production method. Currently, however, the federal government offers a 51-cent-per-gallon subsidy for ethanol production that treats widely different production methods the same, ignoring the important differences between corn ethanol and cellulosic ethanol produced from waste material and refined with renewable energy, for example. The subsidy should be replaced with a producer-based tax credit. By phasing out the per-gallon subsidy and subsidizing ethanol plants based on the type of organic matter they use, the type of fuel they burn, and possibly the market price of oil, the United States can appropriately encourage the best methods with less money.

**Reject proposals to develop high carbon fuels**

Investing in technologies and infrastructure to develop and use high-emission fuels is counter-productive. New coal-to-liquids facilities or production of fuel from oil shale or tar sands will increase the carbon-intensity of transportation fuels and make it more difficult to achieve overall emission reductions. Governments should not offer grants, subsidies or other policy support for these polluting fuels. Money would be far better spent developing low-emission fuels.

**Include transportation fuels within any economy-wide cap on global warming pollution**

As discussed earlier, the transportation sector is the second largest source of global warming pollution in the U.S. Any economy-wide cap on global warming pollution must include transportation fuels. A low-carbon fuel standard can help drive pollution reductions in the transportation sector to ensure that it contributes to overall efforts to lower emissions.

**Require vehicles that are capable of using lower-carbon fuels**

By 2020, all new vehicles should be capable of using lower carbon fuels. Manufacturers could comply by producing hybrid or plug-in hybrid vehicles that operate partially on electricity, internal combustion engines that can consume E85, or other vehicles that operate on fuel with less carbon than gasoline. Widespread use of such vehicles will provide a market for fuel providers who sell low-carbon fuel.

Replacing the entire vehicle fleet in the U.S. takes 12 to 15 years, so policy action is required now to pave the way for the future market of low-carbon fuels. Fortunately, retrofitting vehicles to make them capable of using some alternative fuels is quite inexpensive; estimates range from $100 to $300 for flex-fuel vehicles that can operate on E85.[151]

**Eliminate fuel economy credits for flex-fuel vehicles**

Flex-fuel vehicles can operate with the same efficiency as vehicles with conventional internal combustion engines. However, the current federal corporate average fuel economy (CAFE) requirements allow car manufacturers to meet lower fuel efficiency standards in exchange for producing a small number of flex-fuel vehicles. This trade-off undermines the global warming benefit of flex-fuel vehicles and thus should be ended. America needs both higher fuel economy standards and greater use of low-carbon fuels.

**Encourage construction of additional infrastructure necessary for delivering low-carbon fuel**

Federal tax credits are available for the development of alternative fueling infrastructure. These credits will make it easier to


*New infrastructure, such as this electric vehicle charging station, will make the use of lower carbon fuels possible. (Credit: Jeff Gynane, Dreamstime.com)* accommodate increased use of low-carbon fuels and should be kept in place to appropriately reward such development.

**Support research and development efforts for low-carbon fuels**

The cost of converting cellulosic biofuel feedstocks into fuel limits the competitiveness of ethanol with petroleum products.[152] Research into easier and cheaper methods of refining cellulosic materials will help make those fuels more competitive. Cellulosic feedstock production also needs to be improved with research into better cultivation, including how to increase the yield of cellulosic material from food crops and cover crops.

While federal funding for cellulosic biomass research has increased significantly in percentage terms in recent years, the fiscal year 2007 House budget included only $32.8 million for cellulosic biomass research and development. The federal government should invest in efforts to crack the last remaining technological barriers to cellulosic ethanol production and devise effective strategies for commercial introduction.

# Endnotes


1. Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis: Summary for Policymakers*, February 2007.

2. Ibid.

3. Ibid.

4. R.K. Pachauri and Babu Jallow, Intergovernmental Panel on Climate Change, *Climate Change 2007:*
*The Physical Science Basis*, Powerpoint presentation, 6 February 2007.

5. See note 1.

6. Intergovernmental Panel on Climate Change, *Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability: Summary for Policymakers*, April 2007.

7. See note 1.

8. Ibid.

9. See note 4.

10. See note 1. This range of estimates is based on the range of estimates for various IPCC scenarios, which assume different trajectories for emissions growth.

11. See note 1. Some researchers, such as NASA's James Hansen, suggest that ice-sheet breakup could occur more rapidly than the IPCC suggests. See James Hansen, "A Slippery Slope: How Much Global Warming Constitutes 'Dangerous Anthropogenic Interference?'" *Climatic Change*, 68:269-279, 2005.

12. U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005*, April 2007.

13. U.S. Department of Energy, Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2006*, November 2007; U.S. Department of Energy, Energy Information Administration, *International Energy Annual 2005*, September 2007.

14. U.S. Department of Energy, Energy Information Administration, *International Energy Annual 2005*, *World Carbon Dioxide Emissions from the Use of Fossil Fuels*, June-October 2007.

15. See note 13.

16. U.S. Environmental Protection Agency, *Toxics Release Inventory*, comparison of emissions from "petroleum" SIC code versus all industry, 2005 data as updated 8 June 2007, downloaded 4 January 2008.

17. U.S. Environmental Protection Agency, "County-Level Pollutant-Specific Cancer and Noncancer (Respiratory and Neurological) Risk" (spreadsheet), *Technology Transfer Network: 1999 National Scale Air Toxics Assessment*, downloaded 4 January 2008.

18. J. Pekkanen et al., "Daily Variations of Particulate Air Pollution and ST-T Depressions in Subjects with Stable Coronary Heart Disease: The Finnish ULTRA Study," *American Journal of Respiratory Critical Care Medicine* 161: A24, 2000.

19. Morton Lippmann et al., "The U.S. Environmental Protection Agency Particulate Matter Health Effects Research Centers Program: A Midcourse Report of Status, Progress, and Plans," *Environmental Health Perspectives* 111:1074-1092, 2003.

20. 43 oil spills: Offshore Minerals Management, *OCS-Related Incidents, Spills-Statistics and Summaries: 1996-2007*, downloaded from www.mms.gov/incidents/spills1996-2007.htm, 4 January 2008.

21. Carolyn Marshall, "Oil Spill Spreads in San Francisco Bay," *New York Times*, 9 November 2007.

22. U.S. Department of Energy, Energy Information Administration, *Annual Energy Outlook 2007 with Projections to 2030*, February 2007.

23. $364 billion: U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 2006*, 27 June 2007.

24. U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 2006*, 27 June 2007.

25. BP, *BP Statistical Review of World Energy 2006*, June 2007.

26. See note 24.

27. U.S. Department of Energy, Energy Information Administration, *Petroleum Navigator: U.S. Regular All Formulations Retail Gasoline Prices (Cents per Gallon)*, downloaded from tonto.eia.doe.gov/dnav/pet/hist/mg_rt_usm.htm, 5 December 2007.

28. U.S. Department of Energy, Energy Information Administration, *Petroleum Navigator: Cushing, OK WTI Spot Price FOB (Dollars per Barrel)*, downloaded from tonto.eia.doe.gov/dnav/pet/hist/rwtcm.htm, 5 December 2007.

29. See note 25.

30. 1.07 trillion barrels consumed. 838 billion barrels from mid-1800s to the end of 1997: L.F. Ivanhoe, M. King Hubbert Center for Petroleum Supply Studies, "World Oil Supplies—Production, Reserves and EOR," *Hubbert Center Newsletter*, January 2000. 228 billion barrels from 1998 to 2006: U.S. Department of Energy, Energy Information Administration, *July 2007 Monthly Energy Review*, 18 July 2007, Table 11.1b.

31. See note 24.

32. Alexander Farrell (UC Berkeley) and Daniel Sperling (UC Davis), *A Low-Carbon Fuel Standard for California, Part 1: Technical Analysis*, 29 May 2007.

33. A few researchers dispute the finding that ethanol from any source reduces fossil fuel consumption, and thus could ever reduce global warming pollution. The best publicized criticisms come from work done by David Pimentel at Cornell University and Tad Patzek at University of California Berkeley. These researchers, however, make a number of assumptions about the energy intensity of farming and refining that are questioned by other researchers in the field. In addition, Prof. Pimental and his co-authors ignore any energy savings that stem from the use of ethanol by-products, such as animal feed. For a more detailed explanation of how Pimental's assumptions differ from those of other researchers, see David Morris, Institute for Local Self-Reliance, *The Carbohydrate Economy, Biofuels and the Net Energy Debate*, August 2005; M. J. Bradley & Associates, "Biofuels: The Real Deal—or Not?" *Environmental Energy Insights*, July/August 2006; and Alexander Farrell et al., "Ethanol Can Contribute to Energy and Environmental Goals," *Science*, 311:506-508, 27 January 2006.

34. U.S. Department of Agriculture, *The Economic Feasibility of Ethanol Production from Sugar in the United States*, June 2006.

35. Timothy Searchinger et al., "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change," *Science*, 7 February 2008, DOI: 10.1126/science.1151861.

36. M. J. Bradley & Associates, "Biofuels: The Real Deal—or Not?" *Environmental Energy Insights*, July/August 2006.

37. David Morris, Institute for Local Self-Reliance, *The Carbohydrate Economy, Biofuels and the Net Energy Debate*, August 2005

38. Corn yield: U.S. Department of Agriculture, Economic Research Service, *U.S. Corn Production Costs and Returns per Planted Acre, Excluding Government Payment* (spreadsheet), data for 1960-2006, downloaded from ers.usda.gov/Data/CostsAndReturns/testpick.htm, 19 March 2008. Fertilizer use: National Agricultural Statistics Service, *Agricultural Chemical Use Database*, www.pestmanagement.info/nass/app_statcs3_crop.cfm, 19 March 2008. Fertilizer use: U.S. Department of Agriculture, Economic Research Service, *U.S. Fertilizer Use and Price*, downloaded from ers.usda.gov/Data/FertilizerUse/, 19 March 2008.

39. Nathanael Greene et al., *Growing Energy: How Biofuels Can Help End America's Oil De-*

*pendence*, Natural Resources Defense Council, December 2004.

40. Joseph Fargione et al., "Land Clearing and the Biofuel Carbon Debt" (supporting online material), *Science*, 7 February 2008, DOI: 10.1126/science.1152747.

41. 18 percent less: correction to Alexander Farrell et al., "Ethanol Can Contribute to Energy and Environmental Goals," *Science*, 311:506-508, 27 January 2006. "Corrections and Clarifications," *Science* 312: 1748, 23 June 2006. Twice those: see note 35.

42. Timothy Searchinger, *Response to New Fuels Alliance and DOE Analysts' Criticisms of* Science *Studies of Greenhouse Gases and Biofuels*, 26 February 2008.

43. See note 35.

44. Lee R. Lynd, *Biomass Energy Systems of the Future* (PowerPoint presentation to Growing the Bioeconomy conference, Ames, Iowa), 28 August 2005.

45. Joseph Fargione et al., "Land Clearing and Biofuel Carbon Debt," *Science*, 29 February 2008, DOI: 10.1126/science.1152747.

46. Association of American Railroads, *Freight Rail Works for the Environment*, downloaded from www.freightrailworks.org/media/AAR_LandPage_Factsheets_environment.pdf, 9 January 2008.

47. U.S. Department of Energy, Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the United States 2003*, May 2005.

48. Michael Wang, May Wu, and Hong Huo, "Life-cycle Energy and Greenhouse Gas Emission Impacts of Different Corn Ethanol Plant Types," *Environmental Research Letters*, 2007, DOI:10.1088/1748-9326/2/2/024001.

49. See note 36.

50. Difficult to ship by pipeline: Association of Oil Pipelines, "Increased Ethanol Use Creates Challenges," *In the Pipe*, April 2006.

51. See note 35.

52. See note 32.

53. U.S. Environmental Protection Agency, *Regulatory Impact Analysis: Renewable Fuel Standard Program*, April 2007, and U.S. Environmental Protection Agency, *EPA Finalizes Regulations for a Renewable Fuel Standard (RFS) Program for 2007 and Beyond*, April 2007.

54. U.S. Environmental Protection Agency, *Regulatory Impact Analysis: Renewable Fuel Standard Program*, April 2007.

55. Northeast States for Coordinated Air Use Management, *Health, Environmental and Economic Impacts of Adding Ethanol to Gasoline in the Northeast States*, July 2001.

56. See note 54.

57. See note 55.

58. Ibid.

59. Catherine Cooney, "Higher Ozone Levels from Renewable Fuels," *Environmental Science & Technology Online News*, 16 May 2007.

60. See note 54.

61. Mark Jacobson, "Effects of Ethanol (E85) Versus Gasoline Vehicles on Cancer and Mortality in the United States," *Environmental Science and Technology*, 2007.

62. Frank Black et al., "Alternative Fuel Motor Vehicle Tailpipe and Evaporative Emissions Composition and Ozone Potential," *Journal of the Air and Waste Management Association*, 48:578-591, 1998, and Kelly et al., *Federal Test Procedure Emission Results from Ethanol Variable-Fuel Vehicle Chevrolet Luminas*, Society of Automotive Engineers, International Spring Fuels and Lubricants Meeting, 6-8 May 1996, as cited in Natural Resources Defense Council, *NRDC Statement on New Study of Ethanol (E85) Impact on Air Quality*, 26 April 2007.

63. Jason Hill et al., "Environmental, Economic and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels," *Proceedings of the National Academy of Sciences* 103:11206-11210, 25 July 2006.

64. Ibid.

65. Steve Tally, "Purdue to Study Making Biofuel from Corn Residue," *Purdue News*, 17 June 2002.

66. Food and Water Watch, Network for New Energy Choices, and Institute for Energy and the Environment at Vermont Law School, *The Rush to Ethanol: Not All Biofuels Are Created Equal, Analysis and Recommendations for U.S. Biofuels Policy*, 2007.

67. Heather Stewart, "High Cost of Basics Fuels Global Food Fights," *The Observer* (U.K.), 18 February 2007.

68. Alexander E. Farrell et al., "Ethanol Can Contribute to Energy and Environmental Goals," *Science*, 311:506-508, 27 January 2006.

69. See note 36.

70. The most well-publicized of these are the studies by Pimental and Patzek of Cornell University. Pimental and Patzek, however, exclude consideration of energy saved from beneficial use of by-products (particularly animal feed) from the ethanol production process. As a result, their results have been questioned by many researchers in the life-cycle analysis community.

71. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, *Clean Cities Alternative Fuel Price Report*, October 2007.

72. Brent D. Yacobucci and Randy Schnepf, Congressional Research Service, *Selected Issues Related to an Expansion of the Renewable Fuel Standard (RFS)*, 3 December 2007.

73. Ibid.

74. Ibid.

75. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, *Alternative Fuel Fact Sheet: Do You Own a Flexible-Fuel Vehicle?*, April 2003.

76. Timothy Searchinger and Ralph Heimlich, *Estimating Greenhouse Gas Emissions from Soy-Based U.S. Biodiesel When Factoring in Emissions from Land Use Change*, 28 January 2007.

77. Lee R. Lynd, *The Role of Biomass in Meeting U.S. Energy Needs* (Powerpoint presentation to "Growing the Bioeconomy," Ames, Iowa), 29 August 2005; Worldwatch Institute, *Biofuels for Transportation: Global Potential and Implications for Sustainable Agriculture and Energy in the 21st Century (extended summary)*, 7 June 2006.

78. See note 76.

79. Mark Deluchi, *Life-cycle Analyses of Biofuels* (draft manuscript), May 2006.

80. See note 63.

81. (S&T)² Consultants Inc., *Biodiesel GHG Emissions Using GHGenius: An Update*, prepared for Natural Resources Canada, 31 January 2005.

82. Ibid.

83. Anthony Radich, U.S. Department of Energy, Energy Information Administration, *Biodiesel Performance, Costs and Use*, 8 June 2004.

84. See note 76.

85. See note 81.

86. Jason Hill et al., "Environmental, Economic and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels," *Proceedings of the National Academy of Sciences* 103:11206-11210, 25 July 2006. National Renewable Energy Laboratory, *An Overview of Biodiesel and Petroleum Diesel Life-Cycles*, May 1998.

87. R. L. McCormick et al., National Renewable Energy Laboratory, *Effects of Biodiesel Blends on Vehicle Emissions*, October 2006. U.S. Environmental Protection Agency, *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, Draft Technical Report*, October 2002.

88. Bob McCormick, National Renewable Energy Laboratory, *Effects of Biodiesel on NOx Emissions*, presentation to California Air Resources Board Biodiesel Workgroup, 8 June 2005.

89. See note 36.

90. See note 77.

91. See note 44.

92. See note 71.

93. California Environmental Protection Agency, Air Resources Board, *Staff Report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Gas Emissions from Motor Vehicles*, 6 August 2004.

94. U.S. Department of Energy, Energy Information Administration, *State Electricity Profiles 2006—U.S.*, November 2007.

95. See note 32.

96. M. Q. Wang, Argonne National Laboratory, *Development and Use of GREET 1.6 Fuel Cycle Model for Transportation Fuels and Vehicle Technologies*, June 2001.

97. California Environmental Protection Agency, Air Resources Board, *Draft Technology and Cost Assessment for Proposed Regulations to Reduce Vehicle Climate Change Emission Pursuant to Assembly Bill 1493*, 1 April 2004.

98. Idaho National Laboratory, *Comparing Energy Costs per Mile for Electric and Gasoline-Fueled Vehicles*, downloaded from avt.inl.gov/pdf/fsev/costs.pdf, 16 January 2008.

99. See note 32.

100. Environmental Protection Agency, Clean Energy Environment State Partnership, *State Greenhouse Gas Inventory and Projection Tool*, 2007.

101. Only commercially available: U.S. Department of Energy, *Natural Gas*, downloaded from www.fueleconomy.gov/feg/bifueltech.shtml, 18 January 2008.

102. John O'Dell, "2007 Honda Civic GX: The Phill Is Coming!" *Edmunds.com*, 11 January 2008.

103. M. Q. Wang and H.-S. Huang, Argonne National Laboratory, *A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas*, December 1999.

104. 18 to 24 percent: See note 96. 26 percent: See note 32.

105. See note 32.

106. California Energy Commission, *State Alternative Fuels Plan: Proposed Commission Report*, November 2007.

107. See note 96.

108. See note 25.

109. See note 71.

110. John O'Dell, "2007 Honda Civic GX: The Phill Is Coming!" *Edmunds.com*, 11 January 2008.

111. Fuelmaker, *Frequently Asked Questions*, downloaded from www.myphill.com/faq.htm, 18 January 2008.

112. See note 106.

113. See note 96.

114. National Research Council, National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs*, The National Academies Press, 2004.

115. Ibid and see note 96.

116. See note 114.

117. Average miles per gallon in cars currently is set at 27.5 mpg, per U.S. Department of Transportation, National Highway Traffic Safety Administration, *CAFE Overview: Frequently Asked Questions*, downloaded from www.nhtsa.dot.gov/cars/rules/cafe/overview.htm, 20 December 2007.

118. Tiax, LLC, for the California Energy Commission, *Full Fuel Cycle Assessment: Well-to-Wheels Energy Inputs, Emissions, and Water Impacts*, 1 August 2007.

119. See note 96.

120. See note 114. The NAS scenario for centralized reformation of natural gas would require approximately 66.6 billion cubic feet of natural gas per year to service about 2 million fuel-cell vehicles, while the scenario for decentralized reformation at filling stations assumes consumption of about 37 million cubic feet of gas per year to service 854 vehicles. With approximately 230 million motor vehicles on the road, serving 50 percent of them would equate to an increase in natural gas consumption of about 16 percent of current consumption if the hydrogen is produced centrally and about 22 percent if it is produced at filling stations—not including any reductions in natural gas used in the production of petroleum. Consumption data from U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 2002*.

121. See note 114.

122. California Energy Commission, *AB 1007 Scenarios: Hydrogen Fuel Cell Vehicles*, available at www.energy.ca.gov/ab1007/documents/2007-05-31_joint_workshop/2007-05-31_HYDROGEN_FUEL_CELL_SCENARIO.PDF.

123. Ibid.

124. Ibid.

125. "Worse than Gasoline," *Scientific American*, August 2007.

126. See note 22.

127. Ibid.

128. Natural Resources Defense Council, *Climate Facts: Why Liquid Coal Is Not a Viable Option to Move America Beyond Oil*, February 2007.

129. See note 125.

130. U.S. Department of Energy, *Draft Environmental Impact Statement for the Gilberton Coal-to-Clean Fuels and Power Project*, November 2005.

131. 2.5 gallons: Vivian Stockman, Ohio Valley Environmental Coalition, *Coal-to-Liquid Doesn't Make Sense for Economy, Environment*, 3 September 2006. 5 gallons: Montana Environmental Information Center, *Coal-to-Liquid Fuels: Water*, downloaded from www.meic.org/energy/coals-to-liquid-fuels/coal-to-liquid-fuels-water, 9 January 2008.

132. Susquehanna River Basin Commission, *WMPI PTY, L.L.C., Docket No. 20050905*, Approval Date: 14 September 2005, available at www.ultradirtyfuels.com/srbcpermit.pdf.

133. American Association for the Advancement of Science, *AAAS Policy Brief: Coal-to-Liquid Technology*, 2007.

134. John Deutch, Ernest Moniz et al., Massachusetts Institute of Technology, *Future of Coal: Options for a Carbon-Constrained World*, 2007.

135. Edmund Andrews, "Lawmakers Push for Big Subsidies for Coal Process," *New York Times*, 29 May 2007.

136. See note 134.

137. See note 133.

138. Coal to Liquids Coalition, *What Congress Must Do to Help*, downloaded from www.future-coalfuels.org/congress.asp, 25 June 2007.

139. James Bartis et al., RAND Corporation for U.S. Department of Energy, National Energy Technology Laboratory, *Oil Shale Development in the United States*, 2005.

140. RAND estimates that producing 100,000 barrels per day would require a 1.2 gigawatt power plant. U.S. daily gasoline consumption in 2006 was 9.2 million barrels per day, per U.S. Department of Energy, Energy Information Administration, *Petroleum Navigator*, 24 January 2008.

141. See note 139.

142. Ibid.

143. Doug Struck, "Canada Pays Environmentally for U.S. Oil Thirst: Hute Mines Rapidly Draining Rivers, Cutting Into Forests, Boosting Emissions," *Washington Post*, 31 May 2006.

144. Ibid.

145. Argonne National Laboratory, Oil Shale and Tar Sands Programmatic EIS Information Center, *About Tar Sands*, downloaded from ostseis.anl.gov/guide/tarsands/index.cfm, 31 January 2008.

146. U.S. Department of the Interior, Bureau of Land Management, *Draft Oil Shale and Tar Sands Resource Management Plan Amendments to Address Land Use Allocations in Colorado, Utah, and Wyoming and Programmatic Environmental Impact Statement*, December 2007.

147. Environmental Defence (Canada), *The Most Destructive Project on Earth*, February 2008.

148. See note 145.

149. Many of the recommendations in this section are based on Alexander Farrell (UC Berkeley) and Daniel Sperling (UC Davis), *A Low-Carbon Fuel Standard for California, Part 2: Policy Analysis*, 1 August 2007.

150. Alexander Farrell (UC Berkeley) and Daniel Sperling (UC Davis), *A Low-Carbon Fuel Standard for California, Part 2: Policy Analysis*, 1 August 2007.

151. "$100" from Amy Raskin, Saurin Shah, AllianceBernstein Research on Strategic Change, *The Emergence of Hybrid Vehicles*, June 2006; "$300" from National Highway Traffic Safety Administration, *Report to Congress: Effects of the Alternative Motor Vehicle Fuels Act CAFE Incentives Policy*, March 2002.

152. See note 39.