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# Ethanol: Energy Well Spent

## A Survey of Studies Published Since 1990

Natural Resources Defense Council
and Climate Solutions

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The Natural Resources Defense Council is a national nonprofit environmental organization with more than 600,000 members. Since 1970, our lawyers, scientists, and other environmental specialists have been working to protect the world's natural resources and improve the quality of the human environment. NRDC has offices in New York City; Washington, D.C.; Los Angeles; and San Francisco.

**ABOUT Climate Solutions**
Climate Solutions is a nonprofit organization working to inspire and accelerate practical and profitable solutions to global warming. We build nontraditional partnerships in the Pacific Northwest to increase the use of clean energy and build a dynamic, job-generating clean energy industry. Visit us at www.climatesolutions.org.

This report is based on a study by Roel Hammerschlag of the Institute for Lifecycle Environmental Assessment commissioned by the Natural Resources Defense Council and Climate Solutions. A more detailed and fully annotated report based on the same analysis was published in *Environmental Science and Technology,* a peer-reviewed journal.

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## Introduction

America's dependence on nonrenewable energy sources threatens our security, economy, and environment. America consumes 25 percent of the world's total oil production, but controls only 3 percent of the world's known oil reserves. This means that we must pay high prices for oil imported from some of the most unstable regions of the world and suffer the environmental and public health consequences of our rampant oil consumption – polluted air, smog-filled cities, and the range of threats associated with global warming.

Similar environmental, health, and security concerns surround the other forms of nonrenewable energy. Coal power plants spew toxic emissions such as mercury and carbon dioxide into our air. Nuclear energy production brings national security concerns and uncertainty about how to safely manage the radioactive waste produced. And while natural gas offers a cleaner and safer alternative, like oil it is a finite resource, and much of the gas identified as technically recoverable is either uneconomic to exploit or located in places where its recovery would result in severe ecological damage.

In the face of these questions and concerns, ethanol is earning increasing attention as a potentially cleaner, renewable, and domestically produced alternative to fossil fuels for transportation. However, since ethanol came to national attention after the oil shocks of the 1970s, it has been plagued by questions about its ability to reduce our dependence on fossil fuels. To help resolve these questions, NRDC and Climate Solutions commissioned the Institute for Lifecycle Environmental Assessment to review and compare several of the most influential studies examining how well ethanol leverages nonrenewable energy inputs to deliver renewable energy. For our survey, we chose the 10 most representative works from the U.S. research teams that have studied this issue in depth since 1990.

The full report has been submitted to a peer-reviewed journal, *Environmental Science and Technology*, for publication and should be available to the public in the next few months. In the meantime, this literature review provides a brief summary of our findings.

## Defining the Terminology

Our first task in this effort was to define the terms of the discussion. For the last 25 years, questions about whether and to what extent ethanol could replace fossil fuels in the U.S. energy supply for transportation have been hotly debated in a variety of circles – scientific, political, agricultural, environmental – yet few uniformly defined terms of art have emerged. To compare the results of several studies, we first defined our terms and determined the methodology that we would use to convert the results of various studies into values that could be compared against one another.

For ethanol, the energy return on nonrenewable energy investment, or simply the energy return on investment, is the ratio of the total energy contained in a liter of ethanol to the nonrenewable energy consumed during production of the same amount of ethanol, including cultivating crops, transporting them, and converting them into ethanol. In this equation, if the energy in the ethanol is equal to the nonrenewable energy input to the production process, the energy return on investment value is 1. Values less than 1 mean that more nonrenewable energy was consumed during the production of ethanol than the amount of energy contained in the ethanol—a result that begs the question why not simply use the nonrenewable energy sources directly. Values greater than 1 mean that the ethanol contains more energy than the nonrenewable energy consumed in the manufacturing process—a result that indicates that ethanol successfully captures and delivers renewable energy and can indeed help us reduce our dependence on fossil fuels.

## Corn Ethanol vs. Cellulosic Ethanol

There are two fundamentally different sources of ethanol: starch ethanol produced from the fruit and seeds of plants (for our purposes, corn ethanol produced from the kernels of corn) and cellulosic ethanol produced from whole plants – the leaves, stems, and stalks.

The production of corn ethanol in the United States has steadily increased over the last several years and 95 percent of all ethanol in the United States comes from corn. In 2004, farmers in the United States produced more than 3.4 billion gallons of corn ethanol, consuming 11 percent of the country's corn harvest. The technology for corn ethanol production can be considered mature as of the late 1980s. However, manufacturers continue to make improvements in process efficiency and farmers have reduced the amount of fertilizer required per bushel of corn produced. Taken together, these advancements will gradually decrease the amount of gross energy input to the corn ethanol manufacturing process over time.

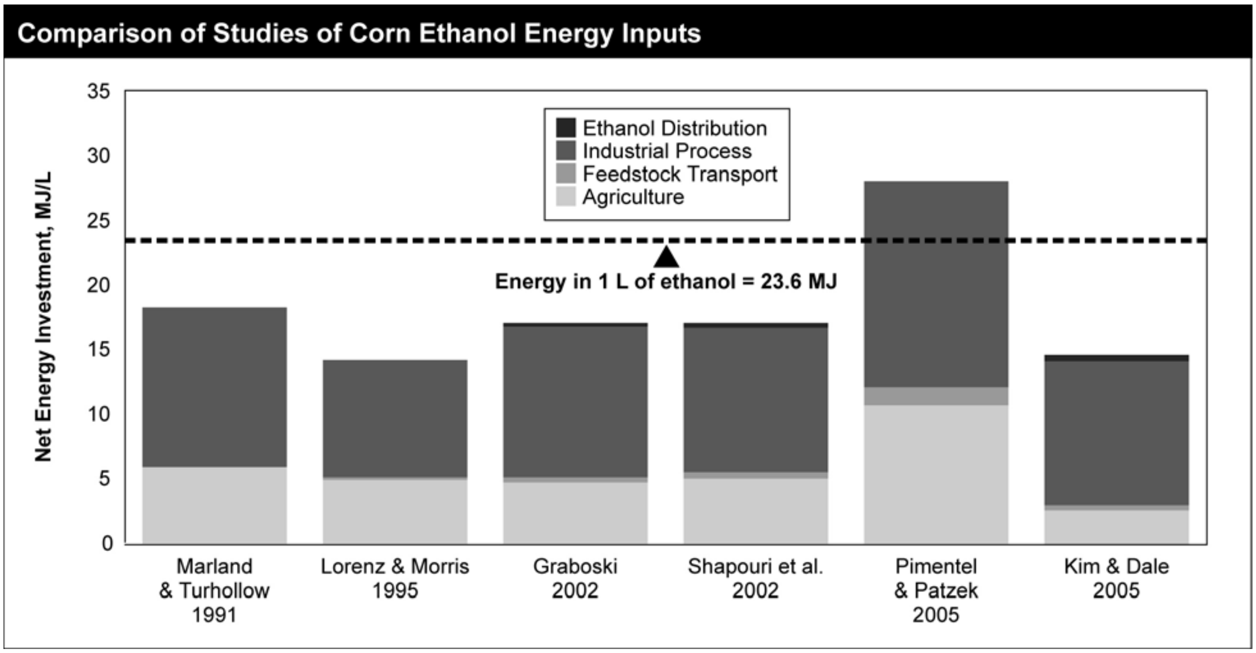
Cellulosic ethanol, meanwhile, can be produced from a number of different crops. The manufacturing processes for this type of ethanol consume the entire plant, including lignin, a chemical compound found in the cell walls of plants that is combusted to fuel the industrial process. Cellulosic ethanol has never been manufactured on an industrial scale, and the technology to produce this type of ethanol is still being developed and is far from mature. Although the studies discussed later in this paper show impressive energy returns on investment for cellulosic ethanol, further developed manufacturing processes for cellulosic ethanol could produce even greater renewable energy returns.

### Corn Ethanol Studies

We reviewed six studies published since 1990 that examine the energy return on investment for corn ethanol. These included studies authored by Marland and Turhollow (1991), Lorenz and Morris (1995), Graboski (2002), Shapouri et al. (2002), Pimentel and Patzek (2005), and Kim and Dale (2005). We calculated the energy return on investment for each study ourselves, using the value of the nonrenewable energy input to the manufacturing process specified by the author of each study and a common total energy output value of 23.6 megajoules per liter of ethanol

Of the six studies that we compared, all but the Pimentel and Patzek study show renewable returns on nonrenewable energy investment for corn ethanol. Energy return on investment values for these five studies ranged from 1.29 to 1.65. The significantly lower energy return contained in the Pimentel and Patzek study can be attributed to a number of factors. First, Pimentel and Patzek reported significantly higher energy inputs to the agriculture, transport, industrial, and distribution components of the ethanol manufacturing process than any other research team over the last 15 years. Specifically, they reported approximately twice the electricity input in the industrial process compared to the other studies and nearly three times the energy input for feedstock transport. Pimentel and Patzek also reported two to three times more upstream energy inputs – energy used by the suppliers of commodities purchased by the farmer or ethanol manufacturer, such as nitrogen fertilizer – than the other studies. Additionally, they included upstream energy burdens not included in the other studies, such as personal energy consumption by laborers and the energy costs of manufacturing capital equipment. Excepting Pimentel and Patzek as an outlier, the energy return on investment values produced in the five other studies indicate that corn ethanol has a solid renewable energy return on its fossil energy investment – its use does indeed help reduce our fossil fuel consumption.

**Figure 1**

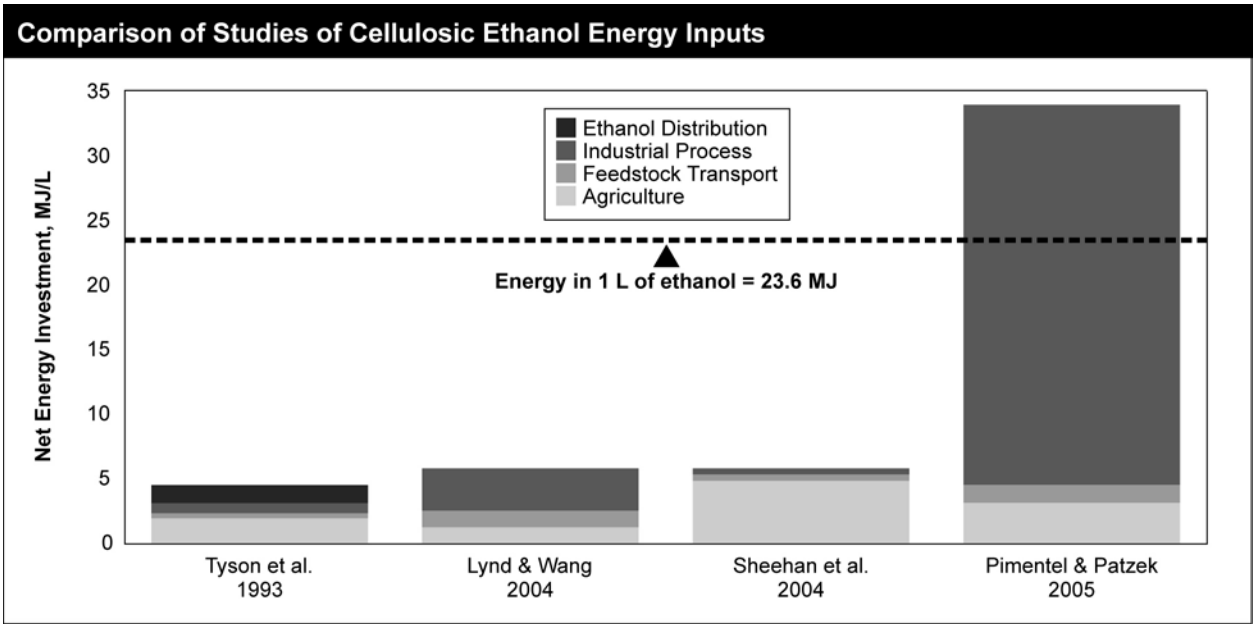



## Cellulosic Ethanol Studies

We reviewed four studies published since 1990 that examine the energy return on investment for cellulosic ethanol. These included studies authored by Tyson et al. (1993), Lynd and Wang (2004), Sheehan et al. (2004), and Pimentel and Patzek (2005). Similar to our review and comparison of the corn ethanol studies discussed above, we calculated energy return on investment of ethanol ourselves, using the nonrenewable energy input value specified by the authors of each study and a common energy output value per liter of ethanol. In contrast to the corn ethanol studies, where all researchers modeled starch ethanol manufactured from corn, the research teams in these studies each modeled different crops.

Of the four studies we reviewed and compared, again all but the Pimentel and Patzek study show substantial renewable returns on nonrenewable energy investment to the production process. Energy return on investment values for these three studies ranged from 4.40 to 6.61, significantly higher than the energy return from corn ethanol. The wide variance of these numbers is consistent with the developing nature of cellulosic ethanol technology and the wide variety of feedstocks available. The significantly lower renewable energy return contained in the Pimentel and Patzek study can be attributed to these researchers' assumption that the industrial energy for manufacturing ethanol would be produced by fossil fuels and grid electricity, rather than by combustion of the lignin that comes to the production facility as part of the crop. All well-developed models of cellulosic ethanol production assume that industrial energy will be produced by lignin combustion – in fact, in most models the heat released by lignin combustion actually exceeds the heat required by the industrial process and can be used to generate surplus electricity.

**Figure 2**




Though manufacturing processes for cellulosic ethanol are not yet mature, the initial energy return on investment values are very encouraging, and the potential exists for even greater renewable energy returns as the technology continues to develop. Indeed, some analysts believe that energy return for mature cellulosic ethanol technology processes could exceed 10.

## Policy Discussion

The energy return on investment measure has quick appeal to policymakers because it provides a straightforward and easily understood threshold value that can be used to gauge the benefit of ethanol production: energy return values greater than 1 mean that using ethanol results in reduced fossil fuel use; values less than 1 indicate that using ethanol would actually increase our fossil fuel use. However, this view oversimplifies the broader worth of biofuels production and use. A full understanding of the role that biofuels such as ethanol might play in America's energy future needs to take into account the relationship of biofuels to the environmental, social, and economic goals of our time. For instance, while energy return on investment does shed some light on a fuel's impacts on greenhouse gas emissions, it tells us nothing about the impacts of oil dependence or land use. Even within greenhouse gas emissions the picture is not as simple as it seems.

### Greenhouse Gas Emissions

Coal has approximately 19 percent more carbon per unit of energy contained in the fuel than oil, whereas natural gas contains about 33 percent less. This means that if coal were used to produce ethanol, ethanol would have to have a better energy return on investment than gasoline—the main fossil fuel it would replace—to produce a net reduction in carbon dioxide emissions regardless. (Gasoline has an energy return on investment of 0.76.) Fortunately, most ethanol is produced using natural gas, and these facilities could actually have a lower energy return than gasoline and still produce a net reduction in carbon dioxide emissions. However, carbon dioxide is only one greenhouse gas; agricultural processes can induce methane and nitrous oxide, both potent greenhouse gases, and some practices can sequester carbon dioxide. Thus, a more complete examination of the impact of ethanol production on greenhouse gas reduction must include an evaluation of the amount of each gas produced under each fuel scenario – gasoline, corn ethanol, and cellulosic ethanol. Still, the examination contained in this paper does indicate that ethanol production can reduce carbon dioxide emissions and that different production methods can produce greater or lesser greenhouse gas emissions.

Because the energy return on investment by itself does not indicate what type of nonrenewable energy is being invested in a process, this metric alone also paints an incomplete picture of ethanol's contribution to reducing our dependence on oil specifically. Fortunately, two of the corn ethanol studies in particular (Graboski and Shapouri et al.) took the additional step of estimating the reduction in crude oil consumption achieved by driving the same distance using ethanol versus gasoline. These studies show that very little petroleum is used in the production process of ethanol and thus a shift from gasoline to ethanol will reduce our oil dependence regardless of its impacts on our use of other fossil fuels.

**Land Use**

Land use arguably is the greatest environmental impact of ethanol production. A sustainable increase in land use to grow the plants used in ethanol production may benefit the U.S. agricultural economy. However, too great an increase in land use could damage the landscape and ecosystems, and in countries with less available farmland than the United States, could compete with land needed for food production. Unfortunately, energy return on investment of ethanol gives us little insight into whether large-scale ethanol production will benefit or harm the U.S. agricultural economy, landscape, or ecosystems. Broadly, we can assume that the higher the renewable energy returns on investment of ethanol for a particular type of ethanol or technology for ethanol manufacture, the less additional land consumed by the manufacture of that ethanol. However, a more meaningful evaluation of the environmental-social interaction of ethanol production and land use requires a more sophisticated analysis of the relationship, such as land area per liter of ethanol.

## Conclusion

Our analysis determined that both corn and cellulosic ethanol production return renewable energy on their fossil energy investments, though the results indicate that cellulosic ethanol production will be preferable to corn ethanol production. On the surface, cellulosic ethanol simply delivers profoundly more renewable energy than corn ethanol. And considered more closely across the social, economic, and environmental factors beyond simple energy return on investment, cellulosic ethanol production promises to consume less petroleum, produce fewer greenhouse gases, and require less land compared to corn ethanol. However, the corn ethanol industry is the foundation from which a much larger biofuels economy will grow. As the energy return on investment shows, corn ethanol is providing important fossil fuel savings and greenhouse gas emissions reductions today, and it is providing an even bigger oil savings.