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COMPREHENSIVE EVALUATION OF IMPACTS FROM POTENTIAL, FUTURE AUTOMOTIVE FUEL REPLACEMENTS

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Abstract

In modern society, everything from transportation to commerce to food supply is heavily dependent on the availability of cheap and plentiful energy supplies. In the past few years many have realized that the traditional sources of energy – oil and gas – are in limited supply and that we need to prepare for the approaching production maxima.

It is in the interest of national economic security to investigate alternative sources of transportation energy before the extraction of existing supplies becomes prohibitively expensive. This meta-study investigates a number of potential fuels and their sources, including

- agricultural solutions - ethanol (corn and cellulosic)
- agricultural solutions - biodiesel
- unconventional refining techniques such as coal-to-liquid
- oil shale retorting and tar sand processing
- traditional petroleum sources

The concentration in the current study is on transportation needs, although it is recognized that building space conditioning and electricity consumption are also significant demands for energy. The results are reported for land use, water use, input-to-output energy ratio, and carbon emissions for each fuel cycle and source. Data are given for the cases of 10, 25, and 50 percent displacements of the 2012 predicted transportation energy needs (i.e., the equivalent of 430 million gallons of gasoline per day). Cradle to grave findings indicate that some novel fuels cannot substitute for conventional fuels without consuming more water or land and emitting more greenhouse gases than fuels in use today. The most sustainable direction for the US transportation fuels sector is suggested.

1 INTRODUCTION

This report investigates a number of potential automotive fuel replacements and their sources, including agricultural solutions (ethanol and biodiesel fuel from crops) and unconventional refining techniques such as coal-to-liquid, oil shale retorting, and tar sand processing. The concentration in the current study is on transportation needs, although it is recognized that building space conditioning and electricity consumption are also significant demands for energy.

In order to estimate how the novel fuels and techniques can offset existing transportation energy demands, it is necessary to examine current and future energy needs. The U.S. Energy Information Agency report *Annual Energy Outlook 2006 with Projections to 2030* [1] provides the annual consumption estimates of many fuel types over the next quarter century. For motor gasoline, the numbers are about 390 million gallons per day in 2006 increasing to about 430 million gallons per day in 2012. Using a typical value of 120,000 BTU per gallon and considering the energy use alone, the 390 million gallons represents 46.8 trillion BTU per year, increasing to 51.6 trillion BTU per year by 2012. That is, research into replacement fuels for automotive use must find a solution capable of providing up to 150 billion BTU per day in the next six years.

The treatment of the noted fuels requires significantly more space than is available in this article. Therefore, we describe the ethanol analysis in some detail typifying the method used for all fuels. However, we do not present details at this level for fuels other than ethanol.

2 ETHANOL

Ethanol has been “branded” as the most likely solution to the energy problems in the United States. With a density of about 6.60 pounds per gallon, the volumetric density of ethanol is about seven percent greater than that of conventional gasoline. However, each gallon of ethanol has lower and higher heating values of about 76,000 BTU and 84,500 BTU, respectively. This is only about two thirds the heating value of gasoline. In other words, ethanol is heavier but has a lower energy content compared to gasoline.

2.1 Extraction / refining

The great majority of ethanol for automotive needs is produced from the fermentation of agricultural products such as corn, potatoes, and other cereal grains. The sugars in the foodstuffs are metabolized in the absence of oxygen to produce ethanol and carbon dioxide. The chemical process for a simple sugar like glucose is

$$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$$

About a third of all ethanol in the U.S. produced from corn using the dry milling process. In the dry milling process the corn feedstock first passes through a hammer mill which grinds it into a fine powder called meal. The meal is then mixed with water and enzymes and passed through cookers where the starch is liquefied. Heat is applied at this stage to enable liquefaction. The mash is then cooled and a secondary enzyme is added to convert the liquefied starch to fermentable sugars. Yeast is then added to the mash to ferment the sugars to ethanol and carbon dioxide. The fermented mash contains about ten percent alcohol plus all the non-fermentable solids from the corn and yeast cells. The mash is pumped to a distillation column where the alcohol is removed from the solids and the water.

Two thirds of the ethanol produced in the U.S. is made with the *wet milling process*. The wet milling process starts with soaking the grain in a water and sulfurous acid mix for 24 to 48 hours. This steeping process helps break the grain down. This is the key difference between wet and dry processes.

2.2 Corn-based and cellulosic ethanol

Ethanol can be produced using any number of crops. Corn is the most dominant food and silage crop grown in the United States, with more annual tons produced than all other crops combined. Obviously, the U.S. agricultural industry is geared towards growing corn and a lot of it. For this reason and because the US government’s ethanol program is focused on corn, this report will concentrate on corn as the agricultural product with the greatest potential for ethanol production. It should be pointed out that the consideration of corn as an ethanol source is not necessarily because it is the best choice from an efficiency or yield standpoint. Rather, there are political forces at work – agricultural and industrial lobbies – that have made the decision to pursue corn as the dominant ethanol source in this country. In fact, corn ethanol will be shown to be one of the least feasible alternative fuel sources.

Estimates of the amount of ethanol that can be derived from corn varies considerably within the available literature. Table 1 shows some of the reported ethanol yields for corn and associated byproducts and demonstrates that the realized yields depend greatly on the material used and the brewing method. The average of all the values in the table is about 94 gallons per ton, very close to the 2.6 gallons per bushel cited as the yield from dry milling of corn grain. In addition, for the purpose of this report, one standard bushel of shelled corn weighs 56 pounds with a moisture content of 15.5 percent.[2] There is a relatively wide range of yields even within a particular crop type due to differences in location, agricultural practices, etc.

Table 1 Reported yields of ethanol for corn and corn byproducts

Component	Reported ethanol yield	Equivalent yield (gal per ton)
Corn grain	2.5 gallons per bushel (wet milling)[a]	89
	2.6 gallons per bushel (dry milling)[a]	93
	124 gallons per dry ton of feedstock[b]	124
	52 liters per 100 kg with fiber conversion [c]	125
	46 liters per 100 kg without fiber conversion [c]	110
Corn cobs	120 grams per kg using hydrolyzation w/o enzymatic enhancement [d]	36
	300 grams per kg using hydrolyzation with enzymatic enhancement [d]	91
Corn stover	113 gallons per dry ton of feedstock[b]	113
	70 gallons per dry ton of feedstock [e]	70

[a] www.newfarm.org/features/0804/biofuels/index.shtml
[b] www1.eere.energy.gov/biomass/ethanol_yield_calculator.html
[c] www.nrel.gov/docs/gen/old/5639.pdf
[d] ift.confex.com/ift/2002/techprogram/paper_10450.htm
[e] www.biomass.govtools.us/pdfs/bcota/abstracts/31/z263.pdf

2.2.1 Land

A large amount of land is dedicated to growing corn in the United States. In 2005 almost 82 million acres were planted with corn of which over 91 percent (75 million acres) was eventually harvested. This is over 117,000 square miles, or about twice the size of all the New England states combined. This yield, combined with a processing efficiency of about 2.5 gallons of ethanol per bushel, gives a figure of 350 gallons of ethanol per acre per year (corresponding to an average yield of 140 bu/acre). Figure 1 illustrates the extent to which existing farm land would have to be committed to producing corn to satisfy various displacements of traditional gasoline by 2012.

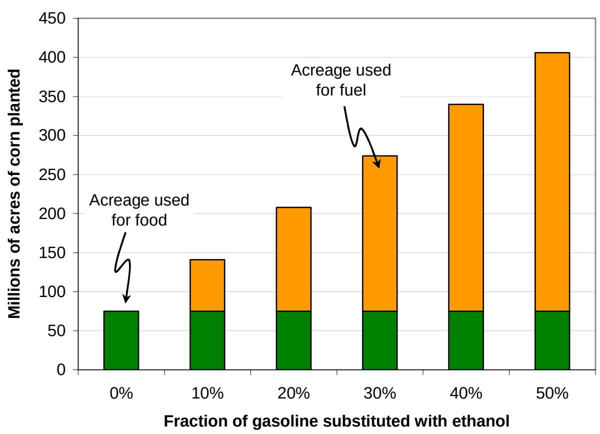

Figure 1 Extra farm land required to satisfy corn-based ethanol production for automotive use by 2012

The National Agriculture Statistics Service cites a value of about 900 million total acres of farmland in the United States of which a third is devoted to harvested cropland.[3] To increase the corn production by 300 million acres would therefore be equivalent to *doubling the total U.S. harvested cropland*. This is a critical point. The farmland of the United States is concentrated in the center region of the country west of the Mississippi River and east of the Rocky Mountains, implying that the land available for growing fuel crops is constrained by the geography of the country.

To better illustrate this point, consider the amount of corn currently produced domestically. Figure 2 shows the mass of corn on a national scale produced for both grain and silage in 2005 (no appreciable quantities of corn are grown in Hawaii or Alaska and they are not included in these figures).

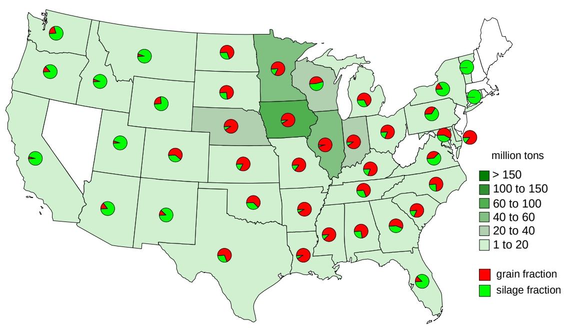

Figure 2 Corn production in 2005

2.2.2 Water

About 13 percent of U.S. automotive energy needs could be met if all of the 2005 corn production were used to produce ethanol. Compare this to the estimated yields if **all** the available cropland in the United States were used to grow corn, which results in about 47 percent displacement of the national energy needs and no cropland remaining for any other harvests. In other words, farmers across the nation would be involved in a monoculture production of corn instead of their traditional plantings. Irrigation requirements, climate, and the inescapable need for other crops relegate this scenario to the category of theoretically possible but logically impossible.

Estimating the water required to grow corn for ethanol production is done by determining the average rainfall during the growing season and adjusting by an "availability factor" that adjusts the rainfall to account for immediate runoff and evaporation.[4] It is assumed that whatever needed water is not supplied by natural rainfall will be provided via irrigation. The increase in acreage determined in the in the previous section is used as the multiplier on the current estimated water use, by state, to grow the additional corn for ethanol production.

The water consumption for ethanol refineries can also be quite large. At approximately 35 gallons of water per gallon of ethanol, the refining requirements are one-third the amount of irrigation water required to grow the corn. Figure 3 shows the total water usage for both irrigation and irrigation plus refinery uses[1].

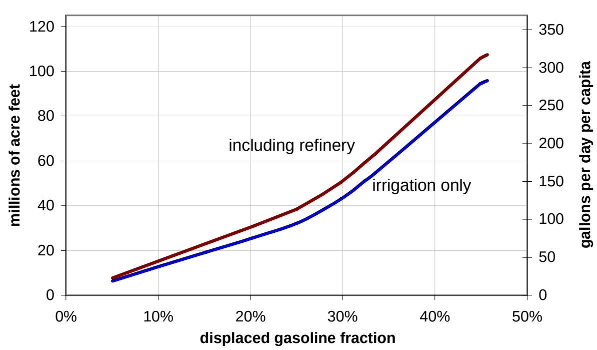

Figure 3 Extra water requirements to irrigate corn for ethanol production

2.2.3 Switchgrass ethanol distinctions

Another potential ethanol feedstock crop is switchgrass, a perennial grass native to North America that can grow five to ten feet tall in a single season and has been used as animal feed and for ornamental purposes. The USDA reports that switchgrass can provide 70 gallons of ethanol per dry ton (through hydrolyzation during the brewing process).[5] The question remains, then, of how much switchgrass can be grown in the United States. The answer is elusive, with about as many estimates as there are research papers. It is likely that the true yield for switchgrass is a function of weather, irrigation, fertilization, and harvesting practices. For the purpose of this study, we assume that the yield of dry switchgrass per acre is three times that of existing yields of dry hay. This multiplier is used for the typical production at the state level, resulting in a national average of about 7.5 tons per acre. The amount of ethanol available for various commitments to the production of switchgrass is estimated by observing how much land is currently used to grow hay based on all grass types (e.g., alfalfa, prairie grass, etc.). Using all available cropland in the United States for a monoculture of switchgrass we could satisfy about three quarters of the domestic 2012 gasoline needs.

The conventional wisdom is that switchgrass can be grown without irrigation or fertilizers. However, when experiments are done, such as those by the Germans trying to determine if switchgrass is an appropriate biomass crop, the conclusions differ: "… crop establishment of switchgrass still poses problems such as long dormancy of the seeds and the need for high temperatures and good water supply for good germination, usually requiring irrigation after sowing.[6]" The Oak Ridge report (ORNL-6944) "A National Assessment of Promising Areas for Switchgrass, Hybrid Poplar, or Willow Energy Crop Production," the regional and state possibilities are noted to be limited: "The Mountain region (AZ, CO, ID, MT, NM, NV, UT, WY) is not presented, as switchgrass, willow, or hybrid poplar production on any large scale is not possible in this region without irrigation. California is also not represented for the same reason.[7]"

We can conclude that it is entirely possible to grow switchgrass without irrigation but, as with most other plants grown without irrigation, the yields could be less than acceptable. For our estimates on the irrigation required to provide useful amounts of switchgrass, we use a value of one fifth the amount of irrigation water estimated to grow hay in the various states. The irrigation requirement for hay is taken from the Nebraska estimates for alfalfa[8] and is about 32 inches per year. This implies that it will take about 6 inches of water per year to grow switchgrass. To commit all of the cropland in the United States to switchgrass for ethanol would require 70 million acre-feet of water every year.

2.3 Energy

The growing of the feedstock for agricultural-based ethanol is only one part of the picture. Regardless of the source, there are some significant issues related to the growing, harvesting, and refining of ethanol that must be addressed when considering ethanol as a replacement fuel. Current agricultural use of diesel fuel is about 3.1 billion gallons per year. The amount

[1] The slope of this line changes because progressively extending the usage of land is assumed to be in the order of most irrigation needed last.

of diesel fuel used per crop will vary depending on the tillage and harvesting requirements; the average on-farm diesel fuel use for corn is about 10 gallons per acre.[9] The existing 75 million acres of corn planted in the U.S. would account for 750 million gallons of diesel fuel, or about a little less than one quarter of all agricultural diesel fuel use. To plant an additional 400 million acres of corn would require use of an additional 4 billion gallons of diesel fuel for the tillage, fertilization, and harvesting. Another way to look at this is that *substituting 50 percent of gasoline with corn-produced ethanol would double the current agricultural use of diesel fuel*.

The great majority of near term ethanol in the U.S. is assumed to be produced by refining corn. There are a number of different interpretations of the energy (and subsequent emissions) required to produce ethanol. Figure 4 shows example energy flows for the production of ethanol by a variety of techniques as discussed in a recent issue of Science magazine. This picture contrasts sharply with those who suggest that ethanol requires far more energy to produce than it would ultimately contribute to light vehicle fuel needs. One Cornell researcher, David Pimental, proposes that ethanol is in fact highly wasteful, consuming 131,000 BTU per gallon produced.[10] That represents a primary fuel input to MJ per MJ of fuel ratio of about 1.7, or over twice that given in the Science article and surpassing the critical ratio of 1.0, implying that it takes more energy to produce than is returned as a fuel. A net energy ratio greater than 1.0 is not unusual for liquid fuels used for transport, building heating or other use. It is the price that one pays for the convenience of liquid fuels and is not the single criterion upon which to make future fuels selections. However, for global sustainability the overall energy ratio needs to be unity or less.

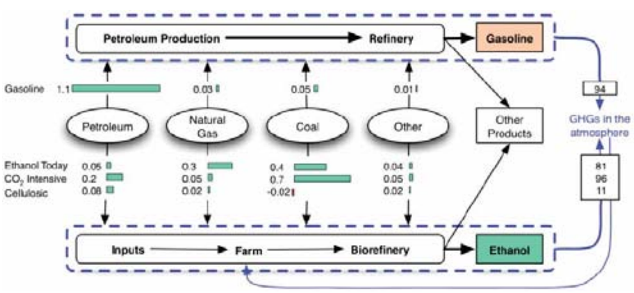

Figure 4 Example energy pathway for production of ethanol[11]

In response to Pimental's research, the U.S. Corn Growers Association performed their own study with assistance from the U.S. Department of Agriculture. USDA estimates that ethanol facilities produce at least 1.23 BTU as ethanol for every fossil BTU included considering all energy inputs related to corn farming, corn transport, ethanol production, and distribution and transport of finished ethanol.[2]

Lorenz and Morris of the Institute for Local-Self Reliance released a report in 1995 that also analyzes the amount of energy used to produce ethanol.[3] Results from this report conflict significantly with the claims from Pimental. Note, however, that the ethanol energy used by Lorenz and Morris is the higher heating value[4] and is therefore somewhat more optimistic than the other calculations in this report. Even in the worst cases the total energy available from the ethanol is approximately equal to the energy used to create the ethanol when a correct apples to apples comparison is made.

2.3.1 Ethanol production

It is expected that the corn refineries of the future will not be the small or farm-based fermenters currently in use but rather large refineries capable of producing millions of gallons per day. The supply of materials and the operation of these refineries both consume energy and generate an effluent stream that must be considered.

Large scale shipments – by rail or by truck – will be needed to supply ethanol refineries with corn. If we consider the state of Nebraska at about 77,000 square miles and assume that the state could support three refineries, this gives about 26,000 square miles of farmland for each refinery, or a rectangular area about 160 miles on a side. We assume that the typical transport distance is then about 150 miles by rail. One gallon of diesel fuel will move one ton of freight about 50 miles by truck and about 200 miles by rail or barge.[5] This is equivalent to about 2500 BTU per ton-mile for trucks and 650 BTU per ton-mile for rail and barges. With a bushel of corn at about 50 pounds, it would take about 2500 BTU to move a bushel of corn from the harvest to the refinery, or about 1000 BTU per eventual gallon of ethanol. This number correlates well with results from previous studies. This transportation energy requirement would lead to an immense use of diesel fuel for the transportation. Even in the least impactful scenarios, the 200 million extra gallons of

[2] http://www.ncga.com/public_policy/issues/2001/ethanol/08_22_01b.htm

[3] Lorenz, D. and D. Morris, *How Much Energy Does It Take to Make a Gallon of Ethanol?*, Institute for Local-Self Reliance (ILSR), August 1995, available at www.carbohydrateeconomy.org/library/admin/uploadedfiles/How_Much_Energy_Does_it_Take_to_Make_a_Gallon_.html

[4] Note that only the LHV is available for transport energy use.

[5] www.eia.doe.gov/emeu/efficiency/ee_ch5.htm

diesel fuel burned per year represents an extra 620,000 tons of carbon released into the atmosphere per year.

Recall that agriculture use of diesel fuel is already about 3.1 billion gallons per year. To substitute 50 percent of our gasoline with ethanol would therefore lead to an additional 30 percent increase in agricultural diesel fuel usage simply to move the corn from the fields to the refineries.

Because ethanol cannot be distributed by steel pipeline since corrosion would significant, additional significant diesel fuel is required for truck and train tank car transport. Space constraints prohibit us from giving the details but they are included in total numbers for ethanol production and distribution.

2.3.2 Energy use summary and carbon emissions

We can now estimate the energy requirements for the production of ethanol from corn and switchgrass. The key metric is the amount of energy needed to grow and refine the ethanol as compared to the energy available in the resultant fuel. As is evident from the research just presented, the actual amount of energy required to grow fuel crops is somewhat of a moving target. For the purpose of this study, energy use is broken down into five categories and are shown in Table 2.

Table 2 Summary of energy calculations for ethanol production (quadrillion BTU per year)

	Corn			Switchgrass		
	Fraction of gasoline displaced			*Fraction of gasoline displaced*		
	10%	**25%**	**50%**	**10%**	**25%**	**50%**
Agricultural diesel fuel use	0.084	0.21	0.43	0.060	0.15	0.30
Irrigation pumping energy	0.028	0.069	0.18	0.013	0.033	0.065
Other farming energy	0.26	0.65	1.3	0.26	0.64	1.3
Refining energy	1.2	3.1	6.1	1.4	3.5	7.0
Transportation energy	0.024	0.059	0.12	0.024	0.059	0.12
Total	1.6	4.1	8.1	1.8	4.4	8.8

The calculation of the amount of CO_2 produced by these energy flows depends greatly on the types and mixes of input energy. For example, the use of diesel fuel, at 130,000 BTU/gal LHV (EIA values) and 6.2 lbs of carbon/gal, results in the release of about 48 lb carbon per MMBTU.

3 Petro-Diesel fuel

From this point forward descriptions of fuel technologies are necessarily curtailed but underlying the reported results are calculations similar to those noted above for ethanol. Diesel fuel is produced from petroleum. The great majority is traditional diesel fuel, created by cracking and refining crude oil. Until recently diesel fuel often contained high concentrations of sulfur that is liberated when the fuel is burned. European and American emission regulations have been modified so that reformulated diesel fuel is required to limit the amount of atmospheric sulfur.

3.1 Land and Water

The land use problems associated with crude oil drilling and refining are more closely associated with pollution and visual impact than of actual land space used. In the first five months of 2006, an average of 243 rotary wells in the United States were in service used to extract crude oil (compared to over 1300 used to harvest natural gas).[12] Even if each wellhead were to occupy ten acres, this is still a very small commitment of land. The same argument can be applied to the refineries.

While the land commitment to petrodiesel may be small, the water consumption is not. Water is used at various points throughout the drilling and refining processes. When the natural subsurface oil reservoir pressure decreases to the point where oil no longer freely flows to the surface, it is common practice to inject water, salt water, steam, or carbon dioxide into the ground to restore the pressure. In 2005, about 1.87 billion barrels of oil were produced domestically, or about 78.5 billion gallons. If we assume that about a third of this came from fields aided by injection wells, and that of those wells about a third used fresh water, then the total freshwater use would be a little more that ten percent that of the total recovered oil: 8.7 billion gallons per year. Compared to the refinery needs, however, this is a very small amount; therefore some uncertainty in these values does not affect the final conclusions very much. Some estimates have between about 3.5 and 5.5 tons of wastewater generated per ton of crude oil in a refinery.[13] If we use a round number of 2 gallons of water necessary to produce and refine a gallon of crude oil, this is equivalent to about ten gallons of water per gallon of diesel fuel.

3.2 Energy use and carbon emissions

The amount of energy used to obtain diesel fuel is dependent on the source of the crude oil (domestic or imported), the means of transportation (rail, barge, or tanker), the refining techniques, etc. The National Renewable Energy Laboratory has completed an extensive study of the life cycle inventory for petroleum diesel fuel[14] that considers all aspects of the mining, transportation, and refining of crude into diesel fuel. The analysis includes both total energy inputs and carbon emissions. The primary energy for the extraction is quite large – more than the energy contained in the oil itself. However, the authors attribute most of this energy to the use of the "associated" natural gas acquired during the extraction process. The external energy inputs exclusive of this gas for the extraction of the fuel are about 7 percent of the energy in the fuel, or about 10,000 BTU/bbl of petroleum or 1250 Btu/gal of diesel fuel assuming eight gallons of diesel fuel per barrel of oil. Refining and diesel fuel transport energy input are equivalent to about 9,600 BTU/gal of diesel fuel, so the total energy input (assuming 8 gallons of diesel fuel per barrel of crude) is about 11,000 BTU required to produce a gallon of diesel fuel. This gives an energy ratio of about 11-12:1. CO_2 emissions are equivalent to about seven pounds of carbon per MMBTU. Fuel consumption in the driving cycle for diesel fuel would add another 48 lb of carbon per MMBTU for a total of 55 pounds of carbon per MMBTU[6].

4 Biodiesel fuel

Biodiesel is a yellowish liquid made from vegetable oils or animal fats and has a high boiling point and low vapor pressure. Biodiesel fuel is often promoted as derivable from used cooking oil. However, the amount of expended cooking oil is far less than that required to make even a minute difference in the consumption of conventional fuels. Nationwide, less than a million gallons of waste fryer oil are produced daily, or less than a quarter of one percent of the amount of gasoline used. It is very likely that biodiesel fuel will be produced in a fashion similar to that discussed in the previous section on ethanol: a feedstock crop will be grown specifically for refinement into automotive fuel. There are a number of potential crops that can be used for this purpose, some of which are listed in Table 3 that cites USDA estimate yields.

Ignoring the exotic – mostly tropical – oils, the standard crops provide anywhere from 40 to 80 gallons of biodiesel fuel per acre. It is useful to compare this to the 10 gallons per acre of diesel fuel that is a typical agricultural energy use today. The energy required to produce biodiesel fuel[7] is less than the energy it produces. However, we still encounter the problems of land use and water use to grow the feedstock for the refineries.

4.1 Land and Water

The land use issues related to biodiesel fuel are not trivial. Recall that the typical yields for ethanol varied from about 300 gallons per acre for corn up to perhaps 700-1000 gallons per acre for switchgrass. Even accounting for a volumetric energy content about half that of biodiesel fuel, the energy yields for ethanol are three to ten times higher per acre than are biodiesel energy yields.

The implications of this are serious based on current agricultural practice: Soybeans are not grown west of the Rocky Mountains. Even the states that do grow soybeans do not devote much cropland to their production, producing about 93 million tons per year, or about 22 percent of the total production of corn grain. If 100 percent of all available crop land in the United States were devoted exclusively to growing soybeans for biodiesel fuel production – and using typical yields for known soybean-producing states and national averages for the other states – this monoculture would produce just over 380 million tons of soybeans a year, capable of being refined into almost 18 billion gallons of biodiesel fuel. Unfortunately, this would provide about an eighth of the transportation fuel requirements. Obviously, soybean-based diesel fuel provides only a partial, temporary and limited solution at best. Other crops provide better returns. Rapeseed, for example, typically yields about three times as much biodiesel fuel per acre than soybeans.

The amounts of soybeans or rapeseed cited above would require a truly immense amount of water to grow and refine. According to the Food and Agriculture Organization of the United Nations, soybeans have a plant life of 135 to 150 days and require between 18 and 28 inches of water.[15] The average of these values, 143 days and 23 inches of

[6] The carbon content upon which these estimates are based is the US average chemical composition from the EIA.

[7] Pure biodiesel (B100) has a LHV of 118,000 Btu/gal whereas 20% biodiesel (B20) has a LHV of 127,000 Btu/gal according to EPA420-P-02-001. 10/2002.

water, corresponds well with the 150 days and 25 inches of water typically allocated to soybeans.[16] Only about 14 percent of all cropland receives the necessary precipitation to grow soybeans without irrigation. Another way to look at the problem is to compare the supplemental water necessary to grow soybeans based on the fraction of available U.S. cropland. Figure 5 illustrates the problem, where the potential displacement of the domestic transportation needs and the required irrigation are shown as a function of the fraction of all cropland devoted to soybeans.

Table 3 Potential biodiesel fuel crops and yields based on USDA numbers

Crop	Yield [a]	Approximate equivalent yield (*gallons per acre*) [b]
Soybeans	30 gallons per ton	39 (using 43.3 bushel per acre)
Soybeans	1.4 gallons per bushel	61 (using 43.3 bushel per acre)
Corn	7.7 pounds of corn oil per gallon	-
Canola	5 gallons per hundredweight	71 using 1419 pounds per acre
Rapeseed	5.3 gallons per hundredweight	80 (using 1500 pounds per acre)
Sunflower	5.3 gallons per hundredweight	83 (using 1564 pounds per acre)
Mustard seed	5.3 gallons per hundredweight	42 (using 787 pounds per acre)
Animal fats and oils	7.7 pounds of yellow grease per gallon	-

[a] Yield for first soybeans entry is from www.msnbc.msn.com/id/10723254; all others are from www.fsa.usda.gov/daco/bioenergy/2002/2002FactorsNFormulas.pdf

[b] Yield per acre from U.S. average values for 2005, found at www.nass.usda.gov

The energy use and carbon emissions for the biodiesel fuel can be calculated in a similar fashion to that of the ethanol crops. In this work we used the industry best practice assuming that such wide-spread use of soy biodiesel fuel would force farmers into bettering their practices. This approach results in a total, life cycle energy input of approximately 80,000 BTU per gallon of biodiesel fuel.

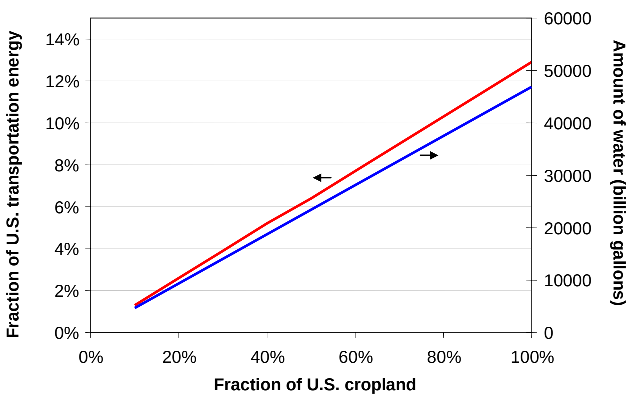

Figure 5 Water required to irrigate a theoretical soybean crop

Delucchi and Lipman present typical emission rates of various pollutants for the biodiesel fuel driving cycle. They report insignificant reductions in carbon dioxide emissions across a wide range of biodiesel/petrodiesel blends, although carbon monoxide emissions were reduced by 20 to 40 percent.

5 Coal-to-liquid and Gas-to-liquid

Another possible source of automotive liquids is the conversion of coal, coal gas, and natural gas to liquid. Coal-to-liquid fuel (CTL) conversion technology has been proven technically and, in the case of South Africa, has been commercially viable for the past 50 years.[17] The Energy Information Administration's Annual Energy Outlook 2006, which predicts U.S. energy production and consumption through 2030, estimates that CTL will provide about 21 million gallons of gasoline per day by 2025, and 33.6 million gallons of gasoline per day by 2030.[18]

The moisture content, composition, and heating value of coal varies largely on geography. The higher the moisture content of the coal, the lower its heating value because energy is required to evaporate the water from the coal as it burns. Greater heating values are also associated with greater carbon content. Carbon and moisture content distinguish bituminous coals from sub-bituminous coals. In general, bituminous coals are found in the Appalachia and Interior regions and sub-bituminous coals are found in the Western region.

5.1 Land and Water

Coal is mined using either surface or underground mining methods, depending on the depth of the coal. Surface mining methods accounted for 67 percent of the coal mined in 2004. The coal produced by the Western region is almost entirely from open-pit surface mines. Surface mines and underground mines in the Interior and Appalachia region have equivalent productivities (measured in tons per miner hour), but these productivities are five times less than surface mining in the West. 19 Of all the domestic coal reserves, about a third is available to surface mining methods. It is difficult to find data that represent the typical amount of land required to mine one ton of coal using either surface mining or underground mining methods. In 2001 the South Powder River Basin open-pit mine in Wyoming contained an estimated recoverable reserve of 905 million tons of coal on a lease area of 27,200 acres.20 This equates to 0.00003 acres/ton coal. In 2004 surface mines in West Virginia produced 55 million tons of coal on about 12,000 acres - this comes to 0.0002 acres/ton coal. Underground mines in Boone County, West Virginia with mining permits on less than 200 acres produced 17 million tons of coal.21 Production of coal from these underground mines requires about 0.00001 acres/ton coal.

Mining water use estimates are likewise difficult – the usual value used is 5.2 gallons per ton coal (mostly for dust control) equates to 0.02 ton of water per ton of coal. Note that the coal liquefaction section will show that the liquefaction process requires about one ton of water per ton coal, thereby domination water consumption in the CTL process.

5.2 Energy and Emissions

The Fischer-Tropsch reaction has a range of hydrocarbon products, and it cannot create motor gasoline exclusively. If the reaction is manipulated to create the most motor vehicle transportation fuel, the percentage of total energy in the products is 51 percent gasoline, 30 percent diesel fuel, and 19 percent kerosene.[22] Because indirect liquefaction is the only commercial solution at present, its conversion efficiency and emissions will be used in the liquefaction model in this report.

Because coal is carbon-rich, creation of liquid fuels from coal requires hydrogen, and the source of hydrogen in the indirect liquefaction scheme is the steam which gasifies the coal. For this and cooling reasons, indirect liquefaction uses a significant amount of water. Sasol's Lurgi gasifiers use about 1.1 tons of steam per ton (moisture included) of coal.[23]

Emissions from indirect liquefaction of coal are primarily related to the composition of the coal consumed. The gasification process allows the removal of 95 percent of the mercury and 99 percent of the sulfur from the synthesis gas so that these elements are not emitted into the atmosphere nor are present in the Fischer-Tropsch fuel products. Additionally, as a result of the gasification process, carbon dioxide is present in concentrated quantities which could lend itself to carbon sequestration methods. .

Unless carbon can be sequestered, the CTL process will emit large amounts of carbon dioxide into the atmosphere. The CO2 emission values shown in Figure 6 are only from production of the CTL fuel and do not count carbon bound in the liquid fuel. AEO 2006 estimated CO2 emissions from all industries are just over 8000 million tons – displacing 50 percent of U.S. gasoline with CTL adds 1000 million more tons CO2 per year.

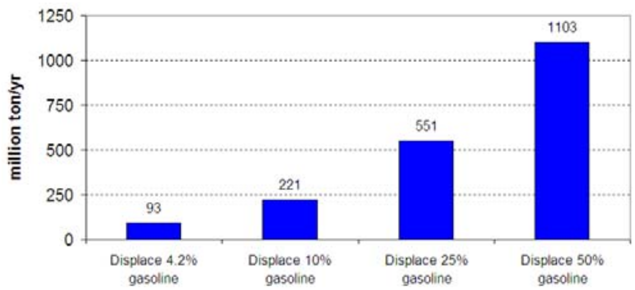

Figure 6 Carbon dioxide emissions in 2025 CTL production

6 Future Fossil Fuels

There are a number of exotic fuel sources that may provide some amount of oil in the future. Some technologies under consideration include heavy crude, oil shale, and tar sands. Currently the technology for direct use of these resources is still under development. One of the reasons is that the extraction and refinement processes are extremely expensive and oil prices to date have not justified more than exploratory research.

Crude oil is widely believed to be the results of the pressurized heating of small, prehistoric marine animals and algae. Over millennia the material turns into a wax-like substance called kerogen and then, through the addition of hydrogen and more heat, into liquid and gaseous hydrocarbons. These hydrocarbons tend to migrate upwards and pool within reservoirs surrounded by impermeable rocks. The *oil window* refers to the temperature range – corresponding to a depth in the earth – where the oil forms. At temperatures lower than the oil window the kerogen is not converted to hydrocarbons; above the oil window the kerogen turns into natural gas. The oil window region is typically around two to five miles below the surface of the earth.[24]

Oil shale is refers to any of the dark shales rich in kerogen that have not been through the oil window. The kerogen can be converted to oil through pyrolysis (heating in the absence of air) and then separated from the surrounding rock through retorting. Some oil shale has been burned directly as a very low-grade fuel, but this is unacceptable for automotive uses.

Perhaps the biggest problem with oil shale is that it has a very low energy density compared to conventional fuels. High quality oil shale would deliver about 30 gallons of oil per ton of rock mined or retorted. This is equivalent to slightly less than four million BTU per ton of rock. Compare this number to the 30 to 38 million BTU per ton of crude oil or the 30 million BTU per ton of coal. It has been pointed out that, pound for pound, oil shale has one third the caloric content of breakfast cereal.[25]

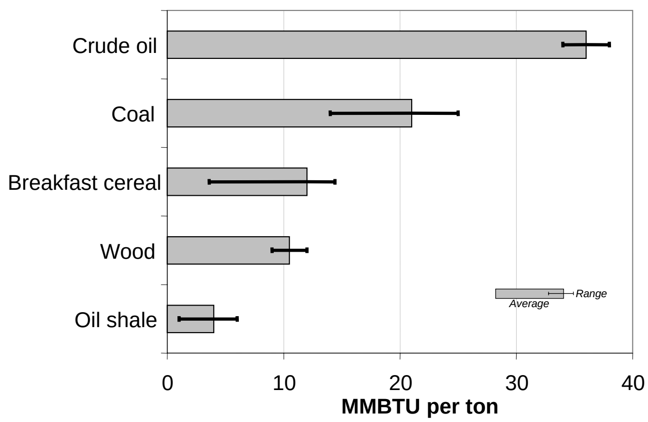

Figure 7 Comparison of energy content of various materials

Tar sands (also called natural bitumen and oil sands) exist around the world. Two of the largest and most readily accessible deposits are in the Athabasca tar sands in Alberta, Canada and the Orinoco tar sands in Venezuela. These two sites combined are thought to contain as much as 60 to 70 percent of the total world-wide oil deposits. However, the same technological challenges exist for tar sands as for oil shale – a huge amount of heating energy is necessary to liberate the oil from the bituminous sands and make it available as automotive fuel.

There are perhaps a trillion barrels of conventional crude oil remaining in relatively easy-to-harvest reservoirs. Only about two percent of this oil is in the United States. However, it has been estimated that there are five trillion barrels equivalent in heavy oil and tar sands, the majority of which is in Canada, Venezuela, and the U.S (see Figure 8). It has been estimated that half the heavy oil and tar sands in the U.S. and Canada could supply these two countries with their oil needs for the next century.

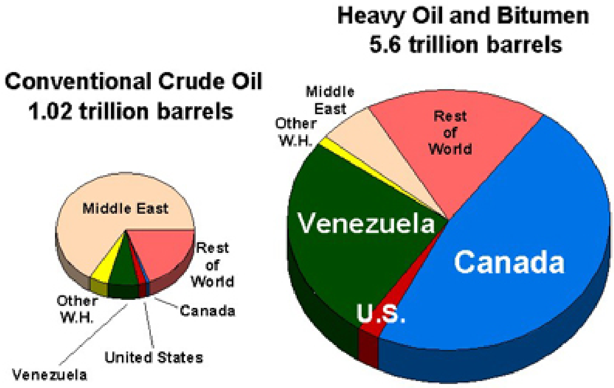

Figure 8 Distribution of remaining crude oil reserves versus untapped heavy hydrocarbon deposits[26]

7 Conclusions

7.1 Summary of results

A summary of the results from this report is found in Table 4. The numbers are reported for land use, water use, input-to-output energy ratio, and carbon emissions. The data are given for the cases of 10, 25, and 50 percent displacements of the 2012 predicted transportation energy needs (i.e., the equivalent of 430 million gallons of gasoline per day). In the case of the fuel crops, the land use and water use values differ for the different displacement fractions since it is expected that poorer soils with greater irrigation needs will be required as the total amount of farmed area increases. The values in the table are notable for a few significant findings. First, the water requirements for the fuel crops are much greater than for the fossil fuel and bitumen sources. Also, the per-acre yields are much lower for the fuel crops, in some cases by many orders of magnitude. While it may be possible to grow enough corn to satisfy the national energy needs, this would effectively create a monoculture farming environment.

It is also important to note that with fuel crops the growing season may affect when the fuel is available. Corn and soybeans may not be available year-round. While it is of course possible to store such crops, the implication is that the breweries and fuel crop refineries will be running at full capacity at harvest time but may be idle at other times of the year (e.g., winter) when the crop supply is not forthcoming. This may have ramifications on the pricing of the fuel and on supply shortages, particularly when one considers that most travel occurs in the summer at a time when the crops are still growing.

Table 4 Summary of fuel source energy studies

		Land use				Water use (gallons)		Energy ratio	CO_2 emissions[a]
Fuel source	**Transportation energy displacement**	**Acres[b]**	**Fraction of U.S. cropland**	**gallons of fuel per acre**	**MMBTU of fuel per acre**	**per gallon of fuel**	**per MMBTU of fuel**	**BTU input per BTU of fuel**	**lb per MMBTU of fuel**
Conventional gasoline	**0-100%**	tens of thousands	very low	-	-	5	45	0.05	60
Conventional diesel	**0-100%**	tens of thousands	very low	-	-	10	80	0.09	60
Corn-based ethanol	**10%**	65 M	20%	370	28	170	2200	0.98	95
	25%	160 M	51%	370	28	180	2300	0.98	95
	50%	337 M	103%	360	28	220	2900	0.98	95
Cellulosic ethanol	**10%**	46 M	15%	515	39	146	1900	0.92	90
	25%	112 M	35%	515	39	146	1900	0.92	90
	50%	228 M	72%	510	39	149	1900	0.92	90
Soybean biodiesel fuel	**10%**	253 M	80%	57	7	900	6900	0.76	50-60
	25%	380 M	120%	57	7	900	6900	0.76	50-60
	50%	1.2 B	390%	57	7	900	6900	0.76	50-60
Coal-to-liquid	**10%**	4,100	very low	~4.4 M	~500,000	3	24	~0.5	~105
	25%	10,300							
	50%	20,600							
Algaculture[d]	**10%**	2.5 M	< 1%	6000	800	50	400	0.2	absorbs waste power plant CO_2
	25%	6.5 M	2%	6000	800	50	400	0.2	
	50%	13 M	4 %	6000	800	50	400	0.2	
Heavy crude	**0-100%**	a few thousand	very low	-	-	~10	~80	~0.25	~55
***In situ* oil shale**	**10%**	7,500[c]	very low	~20 M	~65,000	~6	~45	~0.15	~65
	25%	19,000[c]							
	50%	37,000[c]							
Tar sands	**10%**	48,000[c]	zero	~3 M	~350,000	~5	~38	~0.25	~55
	25%	120,000[c]							
	50%	240,000[c]							

[a] includes driving cycle; carbon emissions are calculated from the chemical composition of various fuels and the appropriate stoichiometric combustion equations with the consumption of CO_2 by photosynthesis (for biofuels) not included so that all fuels are compared on an equivalent basis.
[b] M = million; B = billion
[c] assumes ten years combined for in-ground retorting and productive well life
[d] algaculture added to represent new results that bear on this paper but are not presented herein because of space limitations; for complete details see Kreider[27]

7.2 Imported oil savings and energy security

The whole point behind the identifying of alternative energy supplies is that the current light crude reserves are finite and represent no more than another few decades at current consumption rates. It is therefore instructive to compare these alternative sources of oil to the amount already imported. Table 5 shows the potential of the various technologies to reduce energy imports, with explanations of each fuel type following.

Table 5 Summary of potential to reduce oil imports

Fuel	**Potential to reduce oil imports**
Corn-based ethanol	Low
Cellulosic ethanol	Low
Soybean biodiesel fuel	Low
Coal-to-liquid	High
Heavy crude	Medium
In situ oil shale	Medium to high
Tar sands	Very low

[a] most oil from tar sands would be imported from Canada

7.3 Key conclusions

- Land based biofuels require massive and unavailable land requirements.
- Biodiesel yields are by far the smallest per acre of any land based biofuel.
- Corn ethanol and soy-based biodiesel demands for water are very large; there is no more water in the US thereby disqualifying these fuels on this basis alone.
- All fuels considered have energy returns on energy investments less than 1.0 as is the case with most liquid fuels today; the worst offenders are land-based biofuels when compared to traditional fossil fuels
- Carbon emissions in the life cycle sense are about 50% larger for ethanols than for traditional fossil fuels; such fuels are not the answer to global warming, they make it worse.

Algaculture requires less land, less water and produces more fuel per acre at a better EROI with smaller CO_2 emissions than any other biofuel by a significant margin in all respects; however, it is not included in the table above since it was not discussed in this paper in detail.

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