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EVALUATION OF CRADLE TO GRAVE IMPACTS FROM POTENTIAL AUTOMOTIVE FUEL REPLACEMENTS – AN UPDATE

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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. Recent research has focused on alternative forms of transportation energy including biofuels, unconventional refining techniques, and heavy oil and bitumen. This report is a continuation of earlier research and now considers ethanol produced from municipal solid waste, ethanol from algae, and compressed natural gas.

The data presented are maintained in the same format as previous studies to facilitate comparison between the fuels. 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 life cycle analysis approach presented here is that which should be used as the US moves toward low carbon fuel standards (LCFS) and carbon cap and trade (CC&T) approaches for reducing carbon loading of the environment.

INTRODUCTION

This report builds on earlier research[1] that examined a number of potential automotive fuel replacements and their sources, including agricultural solutions (ethanol and biodiesel fuel from crops) and unconventional fossil fuel refining techniques such as coal-to-liquid, oil shale retorting, and tar sand processing. The concentration in these studies is on transportation end uses, although it is recognized that building space conditioning and electricity consumption are also significant demands for energy. This paper summarizes the earlier research and presents new values for ethanol produced from municipal solid waste, ethanol from algae, and compressed natural gas.

The U.S. Energy Information Agency report *Annual Energy Outlook 2006 with Projections to 2030*[2] provides the annual consumption estimates of many fuel types over the next quarter century. For motor gasoline, the numbers are about 380 million gallons per day in 2009 increasing to about 430 million gallons per day in 2012. Using a typical value of 120,000 BTU per gallon and considering energy use alone (not full life cycle effects), 380 million gallons represents 45.6 trillion BTU per day, increasing to 51.6 trillion BTU per day by 2012. In other words, alternative fuels must be capable of providing about 50 trillion BTU per day.

Gasoline and Petro-diesel fuel

Both gasoline and Diesel fuel are produced by cracking and refining crude oil. 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 were in service in the U.S. to extract crude oil (compared to over 1300 used to harvest natural gas).[3] 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 gasoline and petro-diesel 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, steam, or carbon dioxide into the ground to restore the pressure. There is also significant water usage in the refining of crude oil, estimated to be between 3.5 and 5.5 tons of wastewater generated per ton of crude oil.[4] For the purposes of comparison this report uses two gallons of water necessary to produce and refine a gallon of crude oil.

The amount of energy used to obtain gasoline and 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[5] 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 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 for the extraction of the fuel are about 7 percent of the energy in the fuel, or about 10,000 BTU per barrel. Refining and diesel fuel transport energy input are equivalent to about 9,600 BTU per gallon of diesel fuel, so the total energy input (assuming 8 gallons of diesel fuel per barrel of crude) is about 11,500 BTU required to produce a gallon of diesel fuel. This gives an energy ratio of about 11:1.

CO_2 emissions are equivalent to about three pounds of carbon per MMBTU. The driving cycle for the use of diesel fuel would add another 45 lb of carbon per MMBTU for a total of 48 pounds of carbon per MMBTU.

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.[6] 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.[7]

The amount of land used for coal production is largely site-dependent. 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. Coal produced in 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.[8] Of all the domestic coal reserves, about a third are available to surface mining methods.

Mining water use estimates are typically in the range of five gallons per ton coal (mostly for dust control). If liquefaction is used, then the process requirements can increase to about one ton of water per ton coal.[9]

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 they 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 CO_2 emission values shown are only from production of the CTL fuel and do not count carbon bound in the liquid fuel. AEO 2006 estimated CO_2 emissions from all industries are just over 8000 million tons – displacing 50 percent of U.S. gasoline with CTL adds 1000 million more tons CO_2 per year.

Some have suggested that the waste carbon dioxide (from coal or any industrial process) be combined with nuclear- or solar-produced hydrogen to create synthesized fuels. However, traditionally the energy density of such synthetic gases are about half that of natural gas and are generally not appropriate as an automotive fuel.

Tar sands and oil shale

There are a number of exotic fossil 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 mostly under development, although there are active fields for tar sands in Canada.

Oil shale refers to any of the dark shales rich in kerogen that have not been subjected to sufficient heat and pressure to be converted to oil. 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 obviously 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.[10]

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. 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.

Compressed natural gas

According to the International Association for Natural Gas Vehicles, there are approximately 6.9 million natural gas vehicles (NGV) world-wide, with the United States having approximately 150,000 NGV as of June 2007.[11] Many of these vehicles are configured to run on compressed natural gas (CNG) versus liquefied natural gas. Despite there being only about 1300 CNG refueling stations in the United States, natural gas vehicles are gaining in popularity due to the increasing concerns over gasoline supplies and costs, plus the ability to have a home fueling station using existing natural gas pipelines.

For this report we will cast mileage and emissions in terms of consumed gallons in order to be consistent with the other fuels. This is also necessary since EPA and the manufacturers themselves cite mileages in terms of gallons, or more specifically in *gallons of gasoline equivalent* (GGE).

CNG is metered out in GGE, defined by the National Conference of Weights & Measurements as 2.567 kg of natural gas, or 5.66 pounds.[12] Idaho National Laboratory has an Advanced Vehicle Testing Activity that studies natural gas and hydrogen vehicle emissions. One of their studies[13] has demonstrated the following emission reductions for CNG vehicles using gasoline as the basis of comparison (NMHC refers to non-methane hydrocarbons and HC is the total hydrocarbons):

Emission	**% change**
NMHC	-80
CH_4	+967
HC	+35
CO	-63
NO_x	-34
CO_2	-24

So while there are notable reductions for most emissions, they are not as extensive as those claimed by many natural gas proponents. It is also worthwhile to consider that the methane emissions increase by a factor of ten, although normally these emissions are relatively small and the increase is not significant, even with the effective GHG multiplier of 21. For example, a typical gallon of gasoline emits 19.6 pounds of CO_2 when combusted, while this same gallon of gasoline is responsible for only 0.0037 pounds of CH_4, over 5000 times less by mass, and over 250 times less potent from a GHG perspective.

The Fuel and Energy Source Codes and Emission Coefficients from the EIA program for the Voluntary Reporting of Greenhouse Gases[14] show that gasoline produces 156.4 lbs CO_2 per million BTU while pipeline natural gas produces 117.1 lbs CO_2 per million BTU. This is a 25 percent reduction and agrees quite well with the Idaho National Laboratory observations.

For upstream emissions, we turn to the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006.[15] Emissions related to natural gas production in 2006 are given in the following table (in units of gigagrams per year):

Stage	**CH_4**	**CO_2**
Field production	1317	7203
Processing	568	21204
Transmission and storage	1817	59
Distribution	1176	37

These values are equivalent to 4878 and 28503 Gg for CH_4 and CO_2, or 10.8 billion pounds CH_4 and 62.8 billion pounds CO_2 in that year.

The EIA states that the U.S. produced 23,507,471 million cubic feet of natural gas in 2006.[16] For their calculations, the EPA assigns a density of 19.922 grams per cubic foot to natural gas[17] so the total weight of natural gas produced per year in the U.S. is 1.03 x 10^{12} pounds. At 5.66 lb per GGE this is equal to 182 billion GGE. The upstream emissions can then be estimated as 0.059 lb CH_4 per GGE and 0.35 lb CO_2 per GGE.

The water use and energy return on investment for natural gas can be very difficult to quantify. Natural gas can be obtained as a co-product of oil drilling at very low water cost, or through coal bed methane production at a relatively high water cost. Some estimates for hydrofracturing wells in shale (i.e., using water to crack the rock and liberate the gas) are put at about 3 million gallons per well.[18] Assuming that an average well produces around 250,000 MMBTU of gas in its lifetime[19], the overall water use is on the order of 10 to 15 gallons per MMBTU. It is emphasized that this value can vary considerably depending on the extraction method used.

Similarly, the amount of energy necessary to obtain natural gas depends on how it is extracted. In addition, extraction energy inputs are increasing over time as existing wells and sources are depleted. For example, recent studies claim that the Canadian natural gas fields had a EROI of about 45 to 50 as recently as 1995, while today the numbers are down to 15 to 20.[20]

Ethanol from corn and switchgrass

Ethanol has been “branded” naively 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 than gasoline.

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.

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. Estimates of the amount of ethanol that can be derived from corn vary considerably in the available literature. The initial body of research performed by the authors[1] lists 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 value 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 (where one standard bushel of shelled corn weighs 56 pounds with a moisture content of 15.5 percent.[21])

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.

Only 13 percent of U.S. automotive energy needs could be met if all of the 2005 corn production were used to produce ethanol (leaving none for food). 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.[22] If **all** the available cropland in the United States were used to grow corn the United States would achieve about 47 percent displacement of the national transportation energy needs (but no crop land would remain for any other harvests). This assumes 140 bushels of corn per acre per year, a conversion yield of 2.5 gallons of ethanol per bushel, and an energy content of the resulting ethanol of 76,000 BTU per gallon. 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.[23] 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.

Water consumption for ethanol refineries can also be quite large. Estimates vary between 3 and 35 gallons of water needed for refining a gallon of ethanol. Consequently, the refining needs are about five to thirty percent of the amount of irrigation water required to grow the corn.

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.[24] The 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 could satisfy about three quarters of the domestic 2012 gasoline needs.

The conventional wisdom is that switchgrass can be grown without irrigation or fertilizers, yet experiments by European research groups conclude that “… 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”[25] and studies by Oak Ridge National Laboratory declare that “…switchgrass, willow, or hybrid poplar production on any large scale is not possible without…irrigation.”[26]

In this research the amount of irrigation required to provide useful amounts of switchgrass is taken as one fifth the amount of irrigation water estimated to grow hay in the various states. This implies that committing all cropland in the United States to switchgrass for ethanol would require 70 million acre-feet of water every year.

There are a number of different interpretations of the energy (and subsequent emissions) required to produce ethanol. One researcher claims that ethanol is highly wasteful, consuming 131,000 BTU per gallon produced[27] for a net energy return on investment of about 60 percent. In response, the U.S. Corn Growers Association performed a study with assistance from the U.S. Department of Agriculture in which it is claimed that ethanol facilities produce at least 1.23 units of energy 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.[28] Independent research in the earlier studies by the authors show that the energy ratio for ethanol is very close to unity for both corn and switchgrass.

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 of ethanol: a feedstock crop will be grown specifically for refinement into automotive fuel.

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 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.

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 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 states that grow soybeans do not devote much cropland to their production, producing about 93 million tons per year. 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, or about one-eighth of the national transportation fuel requirements.

The amounts of soybeans cited above would require an immense amount of water to grow and refine. According to the Food and Agriculture Organization of the United Nations, a soybean crop requires between 18 and 28 inches of water.[29] Only about 14 percent of all cropland receives the necessary precipitation to grow soybeans without irrigation.

The energy use and carbon emissions for biodiesel fuel can be calculated in a similar fashion to that of 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.

Biofuels from algae

A somewhat novel approach for producing ethanol and biodiesel comes not from feed crops but through algae produced in either dedicated bioreactors or open ponds. Kreider and Curtiss present a description of the process along with methods for calculating the life cycle emission from algaculture.[30] The open pond and bioreactor techniques assume that carbon-rich power plant flue gas is used for supplementing the growth of algae. One claim is that a 1 GW power plant could produce in the neighborhood of 40 million gallons of biodiesel fuel each year using a 2,000-acre farm of algae bioreactors and that there are perhaps a thousand power plants nationwide with sufficient extra land to construct farms of several hundred to a few thousand acres in size.[31]

Algae use carbon to synthesize carbohydrates, amino acids, sugars, lipids, and a host of other compounds. The amount of algae that can be supported by available carbon is a function of the species of algae, other available nutrients, sunlight, etc. In this study a mass ratio *MR* of 1 pound carbon per pound of algae is used. Some original estimates for open pond farms give numbers higher than this, but it is assumed that the closed bioreactors will provide greater exposure and efficiency of carbon utilization.

The production of biodiesel fuel also naturally allows for the production of ethanol and in perhaps greater quantities than the biodiesel fuel. However, the biggest benefit of biodiesel fuel is that the same engines that run on conventional petroleum diesel can run on biodiesel.

Curiously, the initial research into algae was not as a fuel source but rather as a method for removing carbon from power plant flue gases. The implication here is that the use of algae for fuel production could also help "short circuit" the carbon cycle by removing CO_2 from smoke stacks, albeit for later emission from automobiles. While this may not seem an improvement at first glance, the overall reduction of greenhouse gases from power plants carries great potential, particularly in light of the reality that the automotive emissions would occur anyway.

In preliminary tests at the Redhawk power plant in Arizona, specially designed pipes captured and transported the CO_2-rich effluent gases into bioreactors. It was originally estimated that the production of algae through this process can absorb as much as 80 percent of the CO_2 emissions during the daytime at a natural gas fired power plant.[32] Actual monitored values from this plant during initial tests showed that the algae was able to absorb between 260 and 450 tons of carbon dioxide per acre of bioreactors.[33] Since the initial tests, however, there have been some setbacks with bioreactor technologies at the Redhawk plant:

> *"…current third-generation engineering scale greenhouse grew algae faster than expected, demonstrating again that CO2 recycling and algae productivity can be achieved at scale in our high-technology greenhouses. However, this very success triggered failure, as we could not harvest the rapidly growing algae quickly enough. Their unexpected density limited light and nutrient supply, which caused them to start dying. As a result, the greenhouse had to be shut down."*

In the meantime, however, a number of different companies have cropped up that are looking at algae-to-fuel technologies. There are now over a dozen different companies worldwide attempting to convert algae into fuels. The technology is about as varied as the companies, using bioreactors supplemented with sunlight and nutrients, fermentation tanks that grow algae in a sugar solution without sunlight[34], existing algae-infested polluted water systems[35], wild algae harvested from open-air environments[36], high-density vertical growth systems[37], and many others. The processes proposed for converting the algae into fuels, in addition to the standard fermentation and transesterification, include using high temperatures to gasify the algae[38] and the creation of "green crude" that could be used directly in the current refinery system[39, 40]

Municipal solid waste conversion

Another potential source of ethanol comes from the trash that we throw away every day. Kreider & Curtiss[41] discuss some of the processes and ramifications of the municipal-solid-waste (MSW) to ethanol cycle.

A number of companies are prototyping technologies for MSW conversion, spurred by the ever-increasing economic reward of finding a viable process for producing non-petroleum liquid fuels. Perhaps the method receiving coverage recently is the *Coskata* process currently promoted by General Motors. This process supplies anaerobic bacteria with carbon monoxide and hydrogen in a specialized reactor where the input gases are produced from feedstock consisting of agricultural waste, crops, waste materials such as old tires, and municipal waste streams.[42,43]

In 2007 the American Chemical Society published a seminal paper on this topic, authored by researchers from the University of Toronto and the University of Michigan.[44] In this paper a municipal solid waste-to-ethanol plant was modeled to estimate the energy use and perform a Life Cycle Analysis (LCA) study. The processing plant was a typical facility that used acid hydrolysis and gravity pressure vessel technology. The resulting ethanol was assumed to be used in an E85 blend. The MSW composition used in this study assumed cellulosic material composition (i.e., paper, wood, and yard waste) of about 60 percent.

This report concludes that the life cycle total energy use per vehicle mile with ethanol from MSW is less than that for ethanol from corn or cellulose. They also concluded that the MSW-ethanol use in vehicles reduces net greenhouse gas emissions by 65 and 58 percent compared to gasoline and corn ethanol, respectively. The study also provides estimated energy and emissions for various stages of the MSW-to-ethanol cycle and estimates values for the total upstream energy input of about 43,000 BTU / gal. This represents an energy return on investment of about 1.75 to 1. The upstream emissions of carbon dioxide is then about 13.4 lb CO_2 / gallon.

Similarly, the emissions of SO_X, NO_X, and CH_4 are determined to be 0.033, 0.035, and 0.020 lb per gallon, respectively. When used in an E85 blend the emission numbers are 12.1, 0.029, 0.030, and 0.022 lbs per gallon for CO_2, SO_X, NO_X, and CH_4.

Water and land uses for MSW-to-ethanol production are relatively small. In 2004 the Sanitation Department of the City of New York did an extensive study on different types of technologies for providing a value stream from the huge amounts of MSW generated in the New York metropolitan area.[45] Most of the facilities evaluated are quite small – a plant of a dozen acres or so is capable of processing several hundred tons of MSW per day. Likewise, many of these plants rely on the water inherent in the waste stream for process water and otherwise require only about 100 gallons per ton of waste. At about 77 liters (~20 gallons) of ethanol per short ton (the unit used in the NYC study) this is equivalent to about 5 gallons of water per gallon of ethanol, or about 65 gallons of water per MMBTU of ethanol.

The land use would be equivalent to or less than the refineries needed for processing petroleum. Indeed, there is possible net benefit since the treatment of the MSW would reduce the amount of land required otherwise for landfill.

The carbon dioxide emissions of 13.4 pounds per gallon is equivalent to about 176 pounds of carbon dioxide (~48 lb C) per MMBTU of ethanol produced and delivered. According to Kalogo et al. there is a significant benefit due to the diversion of the MSW from the landfill. Their paper cites a total well-to-wheel value of 103 g CO_2 per km, equivalent to approximately 105 lb per MMBTU.

SUMMARY

A summary of the results from this report is found in Table 2. 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. These values are notable for a few reasons. 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 more than 50% of national transport energy needs, this would effectively create a monoculture farming environment without food production and requiring more water than exists.

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.

Imported oil savings and energy security

The whole point of identifying alternative fuel supplies is that 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 1 shows the potential of the various technologies to reduce energy imports, with explanations of each fuel type following.

TABLE 1 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
Algaculture	Medium
CNG	Medium
Heavy crude	Medium
In situ oil shale	Medium to high
Tar sands	Medium to high[a]

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

TABLE 2 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^{e} 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%**	a few thousand	very low	**-**	**-**	5	45	0.05	175
Conventional diesel	**0-100%**	a few thousand	very low	**-**	**-**	10	80	0.08	175
Corn-based ethanol	**10%**	65 M	20%	370	28	170	2200	0.98	350
	25%	160 M	51%	370	28	180	2300	0.98	350
	50%	337 M	103%	360	28	220	2900	0.98	350
Cellulosic ethanol	**10%**	46 M	15%	515	39	146	1900	0.92	330
	25%	112 M	35%	515	39	146	1900	0.92	330
	50%	228 M	72%	510	39	149	1900	0.92	330
Soybean biodiesel fuel	**10%**	253 M	80%	57	7	900	6900	0.76	240
	25%	380 M	120%	57	7	900	6900	0.76	240
	50%	1.2 B	390%	57	7	900	6900	0.76	240
Coal-to-liquid	**10%**	4,100	very low	~4.4 M	~500,000	3	24	~0.5	~380
	25%	10,300							
	50%	20,600							
Algaculture	**10%**	2.5 M	< 1%	6000	800	50	400	0.2	absorbs CO$_2$ waste
	25%	6.5 M	2%	6000	800	50	400	0.2	
	50%	13 M	4 %	6000	800	50	400	0.2	
CNG	**0-100%**	a few thousand	very low	**-**	**-**	n/a	~10^{d}	~0.1^{d}	~150
MSW-based ethanol	**0-100%**	tens of thousands	very low	**-**	**-**	5	65	0.6	~105
Heavy crude	**0-100%**	a few thousand	very low	**-**	**-**	~10	~80	~0.25	~200
***In situ* oil shale**	**10%**	7,500^{c}	very low	~20 M	~65,000	~6	~45	~0.15	~240
	25%	19,000^{c}							
	50%	37,000^{c}							
Tar sands	**10%**	48,000^{c}	low	~3 M	~350,000	~5	~38	~0.25	~180
	25%	120,000^{c}							
	50%	240,000^{c}							

[a] includes driving cycle
[b] M = million; B = billion
[c] assumes ten years combined for in-ground retorting and productive well life
[d] highly dependent on extraction method and may vary by an order of magnitude
[e] MMBTU = millions of BTU

KEY CONCLUSIONS

Among these fuels one can make another qualitative ranking:

- Land based biofuels require massive and unavailable land requirements.
- Biodiesel yields are the smallest per acre of any land based biofuel.
- Corn ethanol and soy-based biodiesel demands for water are large enough to raise serious questions about their qualifications as fuels.
- Life cycle carbon emissions are about 50% larger for ethanols than for traditional fossil fuels.
- 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.
- The LCA approach is mature enough to be used routinely in LCFS design and CC&T approaches that are expected to be developed in the US in the next decade.

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