Ethanol from Corn: Clean Renewable Fuel for the Future, or Drain on Our Resources and Pockets?

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Abstract. It is shown here that one burns 1 gallon of gasoline equivalent in fossil fuels to produce 1 gallon of gasoline equivalent as ethanol from corn. *Then* corn ethanol is burned as a gasoline additive or fuel. Burning the same amount of fuel *twice* to drive a car *once* is equivalent to halving the fuel efficiency of those cars that burn corn ethanol, and will cause manifold damage to air, surface water, soil and aquifers. The overall energy balance of corn conversion to ethanol demonstrates that 65% of the input energy is lost during the conversion. Carbon dioxide sequestration by corn is nullified when corn ethanol is burned. Therefore, we conclude, subsidizing ethanol from corn as a gasoline oxygenate is one of the most misguided public policy decisions made in recent history.

Keywords: carbon dioxide, corn, ethanol, energy balance, fuel, nitrate, oxygenate, pollution, sequestration

1. Background

Previous government policies, the Alternative Motor Fuels Act of 1988 (AMFA, 1988), and the Clean Air Act Amendments (EPA, 2003a) of 1990, have mandated the use of oxygenates in gasoline in the designated areas of the country, as well as the use of alternative fuels, hoping to improve air quality and reduce greenhouse gas emissions. Nevertheless, in 2001, 130 billion gallons of gasoline were burned in the U.S. (EIA, 2003). Consequently, a quarter of all greenhouse gas emissions and up to three quarters of chemicals that pollute the air, causing smog and health problems, come from motor vehicles (EPA, 2003b). Ethanol is seen by some as the answer to these concerns, providing an environmentally sustainable way of reducing emissions when burning gasoline and helping to decrease oil consumption in the U.S.. The recently passed Energy Policy Act of 2003, requires states to use 5 billion gallons of

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ethanol per year by 2012. But would this legislation, and such a strong emphasis on ethanol, actually benefit us and the environment? The short answer is no, and this paper explains why.

2. Gasoline and Additives

As shown it Table I, gasoline is a mixture (ATSDR, 2003) of up to 50% paraffins (mostly branched), and up to 50% aromatics (benzene, xylenes, and heavier aromatics). Gasoline contains 100-1000 different chemical compounds. In most urban areas, air pollution exceeds the standards mandated by the Clean Air Act, and by law refiners must add to gasoline oxygenating additives like MTBE (methyl tertiary-butyl ether) or ethanol. Oxygenates are oxygen-rich substances that should dissolve well in gasoline and make it burn better, thus reducing carbon monoxide and other emissions.

MTBE is the fuel oxygenate preferred by oil companies, because it is cheap to make from the refinery waste-streams, has about the same heating value as gasoline, mixes well with gasoline, and does not increase the gasoline vapor pressure. MTBE has a terrible taste and odor, and can easily foul up water in drinking wells.

Ethanol is preferred by agricultural and chemical companies for many reasons. However, ethanol does not mix well with gasoline, increases its vapor pressure, can be highly corrosive and, compared with gasoline, has a 34% lower heating value. In other words, ethanol in a car fuel tank tends to mix with any water collected at the bottom of the tank and dispersed in the gasoline. About 1.5 gallons of ethanol are required to replace the energy in 1 gallon of gasoline. For example, to drive on ethanol an average 15-gallon fuel tank in a car must swell to 23 gallons.

Use of ethanol as a gasoline additive has other environmental impacts. Most gasoline is stored in underground tanks, which sometimes leak. Some 400,000 leaks have been reported in the U.S. since 1990 (EPA, 2003c). If a leak occurs, ethanol and gasoline contaminate soil and dissolve into groundwater. Ethanol is liked so much by the soil bacteria that they will metabolize it before anything else, including gasoline hydrocarbons (Powers et al., 2001). When these bacteria no longer consume gasoline components, the subsurface plumes of gasoline spread farther, and can poison more water wells. Hence, presence of ethanol in groundwater may exacerbate problems (Rice et al., 1999) with the existing soil pollution.

Table I. Key properties of gasoline, ethanol and MTBE

Property	Gasoline	Ethanol	MTBE
Chemical formula	C_4 to C_{12}	C_2H_5OH	$(CH_3)_3COCH_3$
Molecular weight (kg/kmol)	100-105	46.72	88.5
Carbon wt. %	85-88	52.2	66.1
Hydrogen wt. %	12-15	13.1	13.7
Oxygen wt. %	0	34.7	18.2
Specific gravity	0.72-0.78	0.796	0.744
Boiling temperature ^{0}F	80-437	172	131
Water solubility	negligible	complete	high
Lower heating value[a], BTU/lb liquid fuel - liquid water	18,000-19,000	11,500[d]	15,100
Lower heating value[a], BTU/gal @60^{0}F	116,000[b]	76,000	93,500
kg CO_2 produced/kg fuel[c]	~ 3	1.9	1.5
g CO_2 produced/MJ in fuel[c]	66-70	71	70

[a] Since no vehicles in use, or currently being developed for future use, have powerplants capable of condensing the moisture of combustion, the lower heating value should be used for practical comparisons between fuels.
[b] Calculated as the mean heating value times the mean density. Can be as high as 120,000 Btu/gal.
[c] Calculated.
[d] (CRC, 1972; API, 1976).

3. Real Problems with Ethanol

It takes a lot of energy from methane, oil, and coal to produce corn, and even more fossil energy to convert the corn feedstock into ethanol (Pimentel, 1991; Pimentel, 2001; Pimentel, 2003; Keeney and DeLuca, 1992). In 2001, corn in the U.S. was harvested from roughly 70 million acres with an average yield of 135 bushels per acre (1 bushel of corn is defined as 56 pounds of corn kernels with 15% of moisture content, equivalent to an 8 gallon bucket.), for a total of 9 billion bushels (USDA, 2003). To produce this corn, farmers applied 9 billion pounds of nitrogen fertilizer, 3 billion pounds of phosphate fertilizer, and 4 billion pounds of potash (USDA, 2003). In Kentucky alone, with corn on 1.2 million acres, 2.7 million pounds of pesticides and herbicides were applied (KASS, 2002).

Table II. Efficiency of biomass conversion to ethanol

Feedstock → Steps in conversion of feedstock to ethanol	Corn starch → glucose	Corn starch → glucose	Wood[a] cellulose → glucose	Wood[a] hemicellulose → xylose
Water content of feed	0.15	0.00	0.00	0.00
Carbohydrate content of feed	0.61[b]	0.70[b]	0.45	0.29
Carbohydrate conversion and recovery efficiency	0.90	1.00	0.76	0.90
Ethanol stoichiometric yield	0.51	0.51	0.51	0.51
Carbohydrate fermentation efficiency	0.75	0.882	0.75	0.50
Distillation efficiency	1.0	1.0	1.0	1.0
Ethanol yield, gal/26.4 kg feed	2.09	**2.66**[c]	1.02	0.51

[a] *Trends in new crops and new uses*. 2002. J. Janick and A. Whipkey (eds.). ASHS Press, Alexandria, VA.
[b] These starch contents are typical of wet and dry corn kernels.
[c] Back-calculated to obtain the 2002 USDA estimate.

When one analyzes the energy inputs to corn production in the U.S., such as fertilizer, pesticides and herbicides, machinery, fuel, irrigation, drying, and transportation, only 3.65 times more energy can be gained from corn than was used to produce it (Pimentel, 2003). In other words, to produce from corn the amount of energy equivalent to 3.65 gallons of gasoline, one has to burn 1 gallon of gasoline equivalent in fossil fuels[1]. Conversion of corn to ethanol by fermentation and distillation requires even more fossil energy. In the end, about 2.66 gallons of ethanol are obtained[2] (Shapouri et al., 2002) from 1 bushel of corn. During the corn conversion process, more fossil energy is used, and additional environmental pollution from the waste streams, water, gases and solids, is generated.

Figure 1 summarizes the overall energy balance of ethanol production from corn. Our calculations are based on the following three assumptions. The *low* heating values of gasoline and ethanol are 116,000

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[1] The calorific values of different fuels: natural gas, diesel, heating oil and coal, are expressed in terms of the calorific value of gasoline.

[2] Most other sources report the yield of 2-2.5 gallons of ethanol per bushel, see Tables II and III.

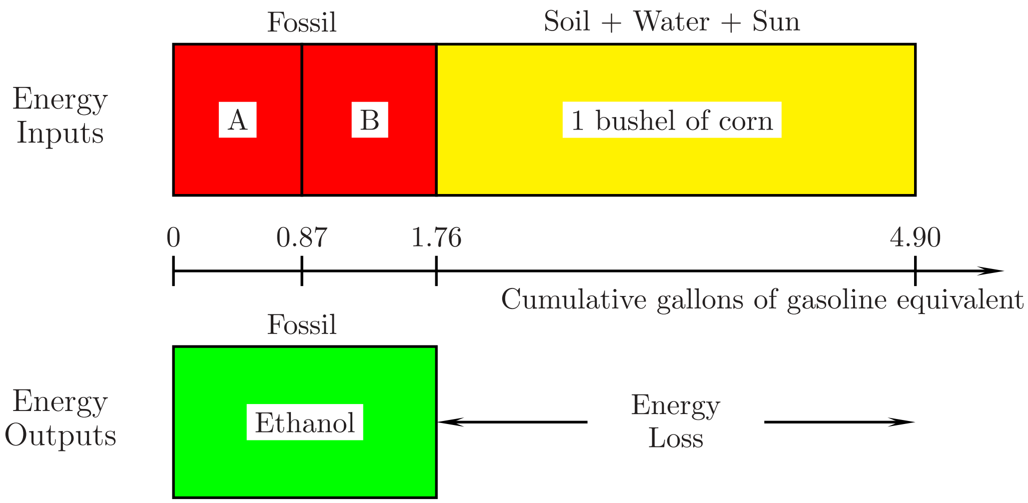

Figure 1. Energy balance of ethanol production from 1 bushel of corn. All energy components are expressed as gallons of gasoline equivalent. Bar **A** is the fossil energy spent on growing corn, and bar **B** is the fossil energy of corn conversion to ethanol. The energy stored in corn is controlled by the availability of soil water and aqueous nutrients (the solar energy is inexhaustible). Therefore, the corn bar represents the energy inputs from the environment, which in return is degraded by the corn. The sun acts as a catalyst, it facilitates the energy sequestration, but remains unchanged by it. For details, see Appendix C.

and 76,000 Btu/gal, respectively, cf. Table I and references therein. The calorific value of moist corn grain is (Pimentel and Dazhong, 1990) 6,500 Btu/lb. Note that this value is much lower than the calorific value of dry corn flour (Ramos et al., 1999): 8,470 Btu/lb.

Table III summarizes the net energy gain or loss from corn ethanol according to different sources. It was first published in (Shapouri et al., 1995), amended in (Shapouri et al., 2002), and here. The last column of this table shows the net energy balance of ethanol production. The negative numbers mean that *more* energy is used to produce ethanol than can be gained by burning it, and the positive numbers mean the opposite. We have critically reviewed and checked for consistency the various estimates listed in Table III. The three papers by Pimentel and others (Pimentel, 1991; Pimentel, 2001; Pimentel, 2003), and the paper by Keeney & DeLuca (Keeney and DeLuca, 1992) report negative net energy for ethanol. The conference paper by Ho (Ho, 1989) is not quite complete, but it also estimates the net ethanol energy to be negative. All others, most notably the USDA, report net energy *gain* from ethanol. We have found Pimentel's numbers to be consistent and

Table III. Estimating the Net Energy Balance of Corn Ethanol

Ref.	Corn yield bu/acre	Nitrogen fertilizer lb/acre	Energy in fertilizer Btu/lb	Ethanol/ Corn gal/bu	Ethanol conversion Btu/gal	Total[1] energy Btu/gal	Energy[1] credits Btu/gal	Net[1] energy Btu/gal
(Pimentel, 1991)	110	136.0	37551	2.50	73687(L)	131017	21500	-33517
(Pimentel, 2001)	127	129.0	33547	2.50	75118(L)	131062	21500	-33562
(Pimentel, 2003)	136	132.0	33590	2.50	58898(L)	99119	6728	-16391
(Keeney and DeLuca, 1992)	119	135.0	37958	2.56	48434(L)	91127	8072	-8,431
(Ho, 1989)	90	NR	NR	NR	57000 (L)	90000	10000	-4000
(Marland and Turhollow, 1991)	119	127.0	31135	2.50	40105(H)	73934	8127	18324
(Morris and Ahmed, 1992)	120	127.0	31000	2.55	46297(L)	75297	24950	25653
(Shapouri et al., 1995)	122	124.5	22159	2.53	53277(H)	82824	15056	16193
(Shapouri et al., 2002)	125	129	18392	2.66	51779(H)	77228	14372	21105

Notes: NR: Not reported
The studies using high (H) and low heating (L) values cannot be directly compared. The USDA studies and the Marland & Turhollow study used incorrectly high heating values and the others used low heating values. Low heating value = 76000 Btu per gallon of ethanol. High heating value = 83961 Btu per gallon of ethanol.
[1] The midpoint is used when studies report a range of values.

reliable. The USDA uses the unjustified high heating value for ethanol and omits some of the energy inputs. The 2002 USDA report builds upon the 1997 Argonne National Laboratory Report (Wang et al., 1997), which is analyzed in more detail in Appendix A.

In all prior analyses, the issue of the solar energy locked in the corn feedstock was put aside. For the reasons explained in Appendix C, the rate of energy accumulation in corn is controlled *not* by the solar energy flux, but by the rate of depletion of fertilized soil, *given sufficient water*. Therefore, corn should be included in the overall balance as much as the fossil energy[3].

By accounting for all major inputs into corn production, Pimentel (Pimentel, 2003) has estimated that today in the U.S. it takes 13,700,000 Btu of fossil energy to produce corn from 1 acre. At an average corn yield of 136 bushels per acre in 2002, this estimate translates to 0.87

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[3] Mr. D. Delaney, http://groups.yahoo.com/group/energyresources/message/-36970, disagrees and states that "The chemical energy of the corn comes entirely from the sun, and is not "invested" in the corn at all. Energy is invested if it would remain available for human disposal if the project (in this case growing the corn and making ethanol) were not implemented at all." Others in the same discussion thread agree with our position, see Mr. Jack Dingler, Message 36963, and many others.

gallon of gasoline equivalent per bushel. The incomplete USDA estimate (Shapouri et al., 2002) of energy required to produce 1 bushel of corn is roughly 60,000 Btu/bushel or 0.52 gallons of gasoline equivalent.

The energy in 1 bushel of corn grain is roughly equivalent to 3.14 gallons of gasoline[4]. So the total energy inputs into the ethanol conversion process are $0.87 + 3.14 = 4.01$ gallons of gasoline equivalent. This is the corn energy capital we are about to spend.

According to the USDA (Shapouri et al., 2002), 2.66 gallons of ethanol are produced from 1 bushel of corn. But ethanol production is *not* energy-free. Also according to the USDA, it costs (Shapouri et al., 2002) $51{,}779 + 1{,}588 \approx 53{,}000$ Btu (0.46 gallon of gasoline equivalent) to produce and transport 1 gallon of ethanol. Some of the corn energy is recovered as distiller's dried grains, corn oil, corn gluten meal, and corn gluten feed from wet milling of the corn grain feedstock. Appendix A has more details. The USDA estimates these energy credits rather liberally (cf. Appendix A) as 14,378 Btu (0.12 gallon of gasoline equivalent) per gallon of ethanol[5]. The USDA report omits *all* environmental impacts of corn conversion to ethanol, and the cost of disposal of waste water and greenhouse gases. In the end, to produce 2.66 gallons of ethanol from 1 bushel of corn the USDA says we have used $(51{,}779 + 1{,}588 - 14{,}378) \times 2.66/116{,}000 = 0.89$ gallons of gasoline equivalent. These 2.66 gallons of ethanol are equivalent to 1.74 gallons of gasoline. This is the outcome of investing our energy capital into ethanol.

The net energy of ethanol conversion is therefore $-(4.01 + 0.89) = -4.90$ gallons of gasoline equivalent in fossil and solar energy plus 1.74 gallons of gasoline equivalent in ethanol, or -3.2 gallons of gasoline equivalent. So in the process of converting industrial corn grain into ethanol, we have lost 65% of the energy inputs. More ominously, we have burned at least as much fossil fuel energy to obtain ethanol, as we may gain by burning it.

In our opinion, at this time the U.S. does *not* need ethanol from corn or any other plant. If, for example, the unnecessary corn were *not* planted, and the corn ethanol *not* produced, the large quantities, 9 million gallons of gasoline equivalent per day, of methane, gasoline, diesel fuel and coal would be saved. From our energy balance it then follows that the energy cost of extra gasoline needed to replace the required 10% of ethanol in some gasoline, would be far less than the energy spent on the complete cycle of corn production and conversion

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[4] Based on the calorific value of corn kernels defined in the assumptions above.

[5] 30% of the energy intensity of corn conversion to ethanol, see Appendix A.

to ethanol. The details of our reasoning are presented in Appendices A – C.

4. Nitrogen Fertilizer Production

Much of disagreement about the energy cost of ethanol production centers on the energy spent to fertilize soil with nitrogen. The nitrogen-rich fertilizers are produced by an energy-intensive nitrogenous fertilizer industry. Ammonia is the most important intermediate chemical compound used to form almost all of the products. Ammonia production is very energy-intensive. It takes twice as much energy to produce one pound of ammonia as one pound of steel (Worrell et al., 1994). Ammonia production accounts for 85% of the energy consumption of the nitrogenous fertilizer industry. In the U.S., the average primary energy cost (Worrell et al., 2000) to produce 1 pound of ammonia is 17,600 Btu.

Practically all ammonia is produced from methane. All carbon in the feedstock methane is converted to carbon dioxide and, as a result, two pounds of carbon dioxide are produced for every pound of ammonia. The energy costs of production[6], and purification, compression and transportation (Worrell et al., 1994) of the feedstock methane are estimated by us to be about 10% of the calorific value of methane. So the corrected energy inputs become 18,700 Btu for 1 pound of ammonia, or 22,700 Btu for 1 pound of nitrogen.

One of the reasons for disagreement among the various calculations of the energy costs of nitrogen fertilizer is inconsistent reporting. All nitrogen fertilizers are *not* created equal; therefore, their energy costs should be expressed using the common reference: nitrogen content. For example, ammonia contains 14/17 of nitrogen, therefore the energy cost of 18,700 Btu/lb of ammonia is equal to $17/14 \times 18{,}700 = 22{,}700$ Btu/lb of nitrogen in the ammonia.

Ammonia is used as feedstock to produce urea, nitric acid and ammonium nitrate. For example, the primary energy needed to produce urea is 28,800 Btu/lb of nitrogen in urea fertilizer (Worrell et al., 1994). Finally the fertilizer must be packaged, transported to the distribution points, and to farms. Let us add another 10% energy penalty for all these activities. Now the energy inputs total 31,700 Btu/lb of nitrogen in urea. It is not clear if the energy of applying the nitrogen fertilizers in the field was taken into account in all the calculations presented in Table III. If it were not (it was included by Prof. Pimentel (Pimentel,

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[6] No one accounts for the energy cost of offshore platforms, and of drilling, operating and cleaning deep gas wells.

1991; Pimentel, 1996; Pimentel, 2003)), then the energy cost of fertilizer would go up again. In summary, our estimate of the total energy per pound of nitrogen fertilizer is close to the latest Pimentel number (Pimentel, 2003), rather than to the 2002 USDA (Shapouri et al., 2002) number.

5. Environmental Impacts of Ethanol Production

Modern corn hybrids are the greediest of plants demanding more nitrogen fertilizer and pesticide than any other food crop (Pollan, 2002). In the U.S., corn production erodes soil about 18 times faster (Pimentel, 1996) than it can be reformed. As a result, the soil is being heavily mined by the intensive corn agriculture. In irrigated acreage, groundwater is being mined much faster than the recharge rate, and midwestern states will face soon (Egan, 2001; USGS, 2003; NPGCD, 2003) a severe water shortage. In 1990, irrigation was responsible for about 96% of the 20 km^3 of water withdrawn from the gigantic Ogallala aquifer (Rosenberg et al., 1999) that underlies the High Plains states. In addition, ethanol production requires huge amounts of water: 35 gallons per bushel of corn (Pimentel, 2003). Ethanol production from corn causes environmental degradation from global warming gas emissions, fertilizer and herbicide run off, and waste water from the production process.

Ethanol-in-gasoline seriously pollutes the air. The reactivity of the combined exhaust and evaporative emissions using the ethanol-blended reformulated gasoline is estimated to be about 17% larger than those using the MTBE-blended reformulated gasoline (NRC, 1999). Ethanol does reduce the carbon monoxide emissions, but increases those of nitrogen oxides (NOx), acetaldehyde, and peroxy-acetyl-nitrate (PAN) (Rice et al., 1999). Finally, all the energy contained in corn-ethanol comes from fossil fuels, with their own emissions. In Appendix B it is shown that carbon dioxide sequestration by corn disappears when ethanol is produced from it, and there is no difference between the corn ethanol fuel and gasoline in CO_2 emissions.

In addition, because of its corrosive properties, ethanol cannot be transported by the existing U.S. pipeline network. Therefore, transportation by train and truck will be the two main alternatives, which will further increase vehicle emissions associated with ethanol use. Ethanol will be blended into gasoline at bulk terminals. The ethanol-containing-gasoline (E10) will then be trucked to the individual gas stations, just as it is today. The only difference will be the E10's somewhat lower energy content and higher price[7].

6. Conclusions

The rate of sequestration of the unlimited solar energy as organic plant matter is controlled by the availability of water in soil, and the minerals dissolved in this water. For the reasons explained in Appendix C, water and soil nutrients are finite and easily degradable. Therefore, we have chosen to include the energy stored in the harvested corn kernels in the overall energy balance of corn conversion to ethanol. With this assumption, 65% of the energy inputs are lost during the entire cycle of corn production and conversion to ethanol.

In addition, as much fossil energy is used to produce corn ethanol as can be gained from it: one burns roughly 1 gallon of gasoline equivalent in fossil fuels to produce 1.5 gallons of ethanol from corn. When this ethanol is burned as fuel, it generates the same carbon dioxide emissions as gasoline (Appendix B), and increases emissions of nitrogen oxides. At the same time, vast quantities of farm land are degraded, aquifers are depleted and contaminated, rivers, and the Gulf of Mexico are polluted with fertilizer and pesticide run-off.

The often-quoted government studies in support of ethanol production from corn, especially the 1997 Argonne National Laboratory Report, seem to be flawed. In fact, our analysis (Appendix A) of the Argonne report, a predecessor to the 2002 USDA report, reveals that the energy costs of corn farming and ethanol production calculated here are supported by the data, but not the conclusions, in both these reports.

The stated goal of adding ethanol from corn to gasoline was to help in cleaning the air we breath and lessen the U.S. dependance on foreign oil. The opposite is achieved. Air is more polluted, and almost as much oil and more methane are burned as without the corn-ethanol. At the same time, additional health hazards are created by the agricultural chemicals, fertilizers, pesticides and herbicides, and by the waste water streams.

The government-mandated goal of 5 billion gallons of ethanol per year (13.7 million gallons per day) by 2012 will be achieved with 2 billion bushels of corn, or over 20% of the current U.S. production.

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[7] The higher ethanol-gasoline price is hidden from the consumer because of the federal and state subsidies in excess of 53 cents/gallon of ethanol (Kheshgi et al., 2000) on top of the corn-grower subsidies. Without these heavy subsidies, ethanol would not be competitive.

The production of this limited volume of ethanol will require the U.S. to burn an *additional* 9 million gallons of gasoline equivalent per day.

It would be beneficial to the U.S., and the world, if an *independent* scientific panel analyzed the complex issues surrounding corn and its products, their relationship to other energy sources, and their social and environmental impacts.

Appendix A: Partial Analysis of the Argonne National Laboratory Report[8]

The debate on the total energy inputs of corn conversion to ethanol has become politically charged and acrimonious[9]. Therefore, I felt that it is worthwhile to scrutinize the 1997 Argonne National Laboratory report (Wang et al., 1997), which is the predecessor of the 2002 USDA report (Shapouri et al., 2002). To my knowledge, the 1997 Argonne report was also endorsed by the U.S. EPA, and used to justify the EPA's support for the increased reliance on corn ethanol in the 2003 Energy Policy Act.

The 1997 Argonne report was commissioned and paid for by the Illinois Department of Commerce and Community Affairs, an organization in charge of promoting ethanol production to provide "a huge boost ($4.5 billion) to the agricultural sector in the Midwest[10]." The report's purpose was to analyze the energy inputs to ethanol production from corn and estimate their environmental impacts. The study focused on Illinois (IL), Iowa (IO), Nebraska (NE) and Minnesota (MN), which collectively produce about half of the U.S. corn and about 95% of the U.S. ethanol. In his endorsement letter, the Governor of Illinois stressed that "the study survived a rigorous review process."

In the Executive Summary, on page i, the authors state: "A weighted energy intensity for corn farming of less than 20,000 Btu/bushel was calculated for the four-state analysis, a value that should be consid-

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[8] This following three appendices were written by T. W. Patzek after the CE24 Freshman Seminar had ended.

[9] The following excerpt is from the article, "Measure to Boost Production Of Ethanol Advances on Hill," by Peter Behr, which appeared in The Washington Post, June 3, 2003. "...The Renewable Fuels Association says Pimentel's data is out of date and inaccurate and his conclusions wrong. And it adds a personal jab. "Dr. Pimentel is out-of-the-mainstream on many issues," RFA says. Studies from the Energy and Agriculture Departments and the Argonne National Laboratory demonstrate that ethanol production creates significantly more energy than it uses, RFA says. "The new data suggests the amount of energy needed to produce ethanol is about 30 percent less than the value of ethanol as a fuel," Early adds."

[10] The words of Governor Jim Edgar, in his endorsement letter.

ered conservative.” On page ii, they state that “Ongoing and future efficiency improvements from retrofits and advanced new plant designs should bring average process[11] energy requirements well under 35,000 Btu/gallon for all mills.” Below, I analyze both these statements in some detail. The authors also state that “dry mills are not economically sustainable absent ethanol production,. . . ” and “Co-product energy use attribution remains the single key factor in estimating ethanol’s relative benefits, because this value can range 0 to 50 % depending on the attribution method chosen[12].”

On page 7 of the Argonne report, Table III-2, it turns out that the weighted energy intensity of about 20,000 Btu/bushel, exactly 19,176 Btu/bushel, accounts only for the authors’ estimate of the fossil fuels used directly in corn farming. These fuels are: diesel fuel and equipment, gasoline equipment, LPG (liquified petroleum gas) equipment, electricity, natural gas, custom work diesel, and hauling. Before analyzing Table III-2, let us use IL and NE as examples, and analyze their corn farming practices, summarized in Tables III-1 and III-3. In 1996, IL planted corn on 11 million acres and achieved corn yield of 132 bushels/acre. NE planted 8.5 million acres and achieved a higher yield of 141 bushels/acre of corn. The overall fertilizer use in lb/acre was, IL: 168(N), 68(P), 97(K), and NE: 150(N), 29(P), 10(K). Thus, IL used 1.8 times more fertilizer per acre, and achieved a lower yield than NE, but the total crop volumes were comparable. With this background information, one would expect the fuel intensity of corn growing to be also comparable, but higher in IL than in NE. In this context, Table III-2 offers a surprise. The reported fuel use in IL, 12,603 Btu/bushel, is *three times lower* than that in NE, 39,693 Btu/bushel! How could this be? Then we find out that 8 major entries in Table III-2 were essentially guesses. So, for example, IL and IA had identical diesel equipment fuel use of $3,954$ Btu/gal, but NE reported 17,792 Btu/bushel, i.e., 4.5 times more! IL and NE reported identical use of gasoline equipment, 3,554 Btu/bushel, while IA and MN both reported 2,665 Btu/bushel. Then, MN and NE used exactly the same amount of LPG fuel, 2,585 Btu/bushel. Finally, IL reported use of 437 Btu/bushel in natural gas (an unreasonably low number), NE 11,716 Btu/bushel (*twenty seven times more*), and the other two states did not report any natural gas use. So the weighted estimate of natural gas use that entered the final Argonne calculation was only 2,759 Btu/bushel. In summary, Table III-2 in the Argonne report, which contains the main fossil fuel re-

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[11] Of corn conversion to ethanol, TWP.

[12] In plain English, an estimate of the energy costs of ethanol production can be cut in half by attributing some of the corn conversion costs to other by-products and processes.

quirements of corn farming, seems to be somewhat contrived. In fact, I suspect that the NE fossil fuel energy inputs are closer to reality than the IL inputs.

To their estimate of energy-intensity of corn farming, the authors apparently forgot to add the costs of nitrogen, phosphate and potash fertilizers, whose application rates are listed in Table III-3 of their report. A short calculation, using the specific fertilizer energy intensities on page 8, yields another 25,000 Btu/bushel. In the Argonne study, the specific energy of producing nitrogen fertilizer is 21,000 Btu/pound of nitrogen. The Argonne estimate is substantially lower than the ones proposed by us. On page 8, the authors claim that "...there has been a substantial improvement since the early 1980s, with net energy intensity[13] being reduced by up to 40 percent on average." It may be so, but Dr. Ernst Worrell (Worrell et al., 1994; Worrell et al., 2000), tells us that (1) the U.S. nitrogen fertilizer plants are in general relatively old and not very efficient; (2) the engineers often do not know their plant efficiency; and (3) the capital costs for a new greenfield ammonia plant are estimated at $300 per tonne annual capacity, and the profit margins in fertilizer plants are so thin[14] that no new investments are forthcoming.

The authors also forgot to add the energy cost of pesticides and herbicides. From their Tables III-4 and III-5, these costs are 2,200 and 160 Btu/bushel, respectively. So far the energy intensity of corn production is $19{,}176 + 25{,}010 + 2{,}173 + 156 = 46{,}500$ Btu/bushel, and not the 20,000 Btu/bushel in the Executive Summary.

Corn, fertilizers, pesticides, herbicides, diesel fuel, gasoline, LPG, coal, etc., must all be transported. The authors estimate that 50/50 transport by barge and rail costs 294,940 Btu/ton of corn or 8,300 Btu/bushel. On page 13, they further estimate the truck energy intensity to be $100{,}000 - 220{,}000$ Btu/ton of corn, depending on the truck weight. With a 50/50 split, transport by truck adds another 4,600 Btu/bushel. So far we have accumulated $46{,}500+8{,}300+4{,}600 = 59{,}400$ Btu/bushel of corn.

Finally, apparently, in IL, IA, MN and NE no energy is spent on the irrigation of corn fields, and the authors side-step this issue altogether. If there were some irrigation[15] in these four states, it might add another (Pimentel, 2003) 3,500 Btu/bushel of corn in energy expenditures. Please note that the water-related energy expenditures are relatively small.

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[13] Of nitrogen fertilizer production, TWP

[14] With the price of methane doubling in 2003, these margins grew even thinner.

[15] As Mr. S. Shaffer of the California Department of Food and Agriculture points out, some 90% of the corn grown in the U.S. is rain-fed.

The total energy cost of producing corn is not 20,000, but 63,000 Btu/bushel of corn, or 0.54 gallons of gasoline equivalent. I remind the Reader, that by missing some of the energy inputs[16], and by underestimating the fuel and nitrogen fertilizer costs, the 20,000 Btu/bushel Argonne estimate, corrected here to 63,000 Btu/bushel, is still too low[17]. A more appropriate estimate of the total energy cost of growing corn is our 0.87 gallons of gasoline equivalent per bushel of corn.

Now, let us focus on the energy cost of corn conversion to ethanol by wet-milling. In this process, the water-soaked corn kernels are ground, their fiber and germs are separated from starch, the starch is hydrolyzed enzymatically to glucose, the glucose is fermented to an industrial beer, and the beer is distilled and dehydrated to obtain ethanol. These complex wet-milling operations require massive amounts of heat, mostly from burning coal[18], and huge amounts of process water (35 gallons per bushel of corn (Pimentel, 2003)).

The energy costs of corn conversion to ethanol, listed in Table III-9, are 48,862, 46,380, 54,977, 51,000 – 53,000, 53,089, 45,000 – 50,000, 40,000 – 50,000 Btu/gallon of ethanol, depending on the study. There is also one unverified number, 34,000 Btu/gallon, based on an oral communication from someone by the name C. Reeder, who apparently worked at Archer Daniels Midland (ADM) Corn Processing, Decatour, IL. Then, on page 17, the authors talk about the benefits of conversion from coal fuel to methane and cogeneration, and state: "In general, a reduction of 10% in energy use is readily achieved by cogeneration systems[19]. With this reduction rate, if all plants employ cogeneration systems[20], the total energy consumption in ethanol plants would be …40,300 Btu/gal for wet milling plants. In our base case analysis, we assume that …100% of wet milling plants employ cogeneration systems…"

Let us parse these statements. The arithmetic mean of all entries in Table III-9, including the arbitrary number from ADM, is 47,800 Btu/gal. The authors then take $0.9 \times 47{,}800 = 43{,}000$ Btu/gal as

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[16] Such as manufacturing and amortization of field machinery, tractors, trucks, irrigation systems and pumps, corn silos, buildings, roads, fertilizer plants, herbicide and pesticide plants, methane gas infrastructure, barges, railroads, environmental damage control, etc. (Pimentel, 2003).

[17] If the contrived mean fuel energy intensity of 19,176 Btu/bushel were replaced with the NE data, the Argonne estimate would jump to 0.71 gallon of gasoline equivalent per bushel.

[18] According to Table III-8 in the Argonne report coal's share of the total energy costs of ethanol production is 80% now, and in the near future.

[19] This 10% reduction was apparently disclosed to the authors by Dr. Michael S. Graboski, but there is no published corroboration.

[20] Currently, they do not, TWP.

the number they will use to justify the energy benefits of ethanol production. Note that the said 43,000 Btu/gal becomes 40,300 in the Argonne report by a simple reversal of digits, a nice savings of 7% of the energy inputs. In my estimate, I will omit the outlier from a source with an obvious conflict of interest, and use the mean of all other studies, 50,000 Btu/gal, also discounting the co-generation savings as based on hearsay. These 50,000 Btu/gal of ethanol, translate into 1.15 gallon of gasoline equivalent per bushel of corn. Instead, the authors use in their Executive Summary the single, undocumented outlier from ADM, $\approx$ 35,000 btu/bushel, to represent the typical energy costs of corn conversion to ethanol. In fact, the subsequent 2002 USDA report, (Shapouri et al., 2002), uses 51,779 Btu/gal as the typical energy of the conversion.

Now we must add the ethanol transportation costs and subtract energy credits. The Argonne report is silent on the energy intensity of ethanol transportation from ethanol plants to distribution centers and end-users. To first order, we can use the just calculated transportation energy intensity by rail, barge and truck, 8,300 + 4,600 = 12,900 Btu/bushel of corn and divide it by the factor of 2.66 gallons of ethanol/bushel. The approximate result is 4,800 Btu/gallon of ethanol, *three times* as much as the 1,588 Btu/gal calculated in the USDA report.

I *agree* with the Argonne report that dry milling of corn is uneconomical given its only byproduct, dried distiller's grain (DDG), is a low quality cattle feed that would never be able to compete with soybean, and is worth only 6,700 Btu/gal (Pimentel, 2003) in energy credits. A wet milling plant, in contrast, can produce starch, glucose, and high-fructose corn syrup (HFCS), one of the most pervasive and harmful human food additives in the U.S. history (Pollan, 2002; Elliott et al., 2002). Because HFCS competes with ethanol for the starch and glucose, it gets no credit from ethanol production.

For a wet milling plant, the Argonne report assigns roughly 70% of the total energy outlays to ethanol production (see Footnote 12), and 30% to byproducts: corn gluten meal and germ. Corn gluten meal has the same value as a cattle feed as DDG. The protein content of the gluten is about 45%. Soybean meal that corn gluten is substituted for contains about 50% protein. As observed by Prof. Pimentel (Pimentel, 2003), the corn protein resulting from the processing of corn for ethanol production is replacing soybean meal. *Thus, we should calculate the benefits of corn protein based on its replacement of soybean protein.* Soybean protein requires significantly less energy to produce than corn protein because the nitrogen fertilizer can be omitted in production. Soybeans will supply their own protein by nitrogen fixation without nitrogen fertilizer. Corn oil can be further extracted from corn germ by using solvents. The two byproducts are obtained after grinding (germ) and washing (gluten) corn kernels to separate starch.

It is hard to imagine that the drying process and energy content of corn gluten and germ should be given 30% of the entire energy required to produce anhydrous ethanol. Bulk of this energy is spent on distilling (up to three times) the corn beer, and dehydrating the 95% ethanol obtained in the distillation to 99.8%. It is also *inconsistent* for Argonne to say that DDG in dry milling is uneconomical without ethanol, but the functionally identical corn gluten meal should get a huge energy credit. I will therefore assign the same energy intensity to the byproducts of wet milling as to those of dry milling, 6,700 Btu/gallon of ethanol. But corn gluten meal must be transported from the ethanol plant back to farms. I will use the same estimate of the ethanol transportation costs, 4,800 Btu/gal, and multiply it by 0.3 to adjust for the gluten volume, obtaining 1,440 Btu/gal.

Finally, the corrected energy intensity of corn conversion to ethanol in the Argonne report should be $(50{,}000 + 4{,}800 - 6{,}700 + 1{,}440) \times 2.66/116{,}000 = 1.14$ gallons of gasoline equivalent. If one adds the two corrected Argonne estimates of the fossil energy costs of producing 2.66 gallons of ethanol from 1 bushel of corn, namely, 0.54 gallon to grow the corn, and 1.14 gallons to convert it to ethanol, one obtains 1.68 gallons of gasoline equivalent per 2.66 gallons of ethanol, or 1.74 gallons of gasoline equivalent as ethanol. *Thus, the corrected Argonne estimate of the energy inputs of corn conversion to ethanol and our estimate are almost identical.* Now remember, to estimate the conversion energy of corn to ethanol, we have used the 2002 USDA numbers (Shapouri et al., 2002), which are based in large part on the approach and data in the 1997 Argonne report. A more appropriate combination of the energy inputs, would be to add 0.87 gallon of gasoline equivalent for corn production and 1.14 gallons of gasoline equivalent for corn conversion, obtaining the energy requirement of 2 gallons of gasoline equivalent to produce ethanol from one bushel of corn. The last estimate is very close to those by Pimentel (Pimentel, 1996; Pimentel, 2001; Pimentel, 2003).

Appendix B: Some environmental costs of ethanol from corn

Let us first look at the greenhouse gas emissions. Carbon dioxide is sequestered in corn starch by the following schematic reaction: Solar energy$+ 6CO_2 + 6H_2O \rightarrow (CH_2O)_6 + 6O_2$. The glucose (hydrolized starch) fermentation to ethanol then progresses as $(CH_2O)_6 \rightarrow 2C_2H_5OH + 2CO_2$. Therefore, the net CO_2 sequestration with ethanol production

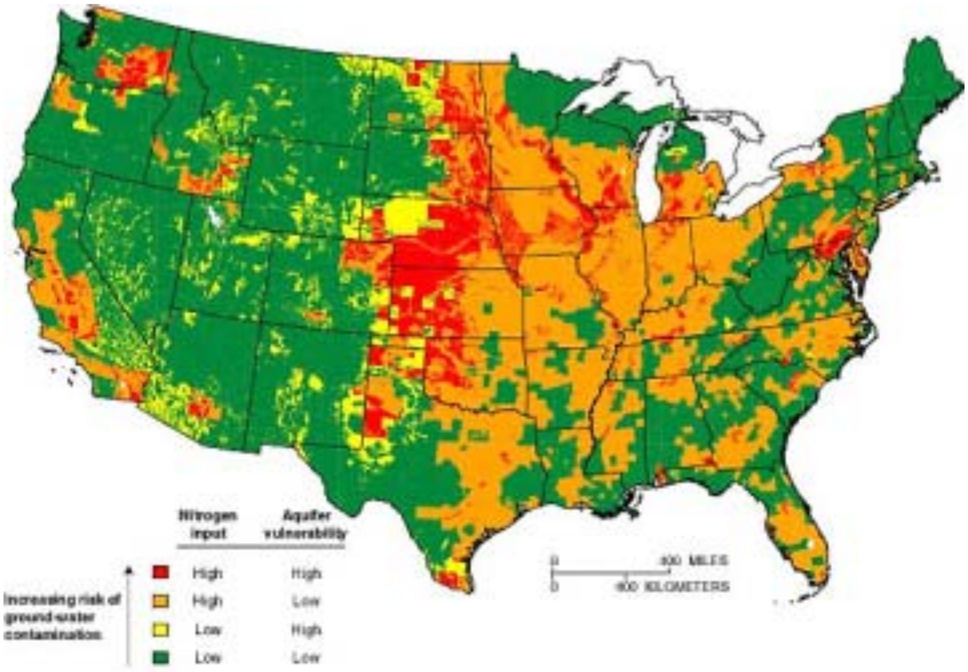

Figure 2. Contamination of groundwater with nitrate mostly from fertilizer. Source: The Quality of Our Nation's Waters, U.S. Geological Survey Circular 1225 - Nutrients and Pesticides, http://water.usgs.gov/pubs/circ/circ1225/index.html.

is $(6-2)/2 = 2$ moles of carbon dioxide per mole of ethanol. As we have just demonstrated, the energy cost of ethanol production is equal to its energy content destroyed by burning it: $C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$, and the two moles of sequestered CO_2 are cancelled by at least two moles of CO_2 generated by burning fossil fuels to produce one mole of ethanol from corn[21]. *Then* we burn the ethanol, and a rudimentary calculation shows that, per mile driven[22], one generates the same amount of CO_2 as by burning gasoline. Furthermore, the reduction of carbon monoxide emissions due to ethanol in gasoline is an illusion in view of the vast quantities of fossil fuels, especially coal, burned to obtain this ethanol.

The corresponding NO_x emissions are probably multiplied many times when the nitrogen fertilizer production and soil emissions are

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[21] For example, 3 moles of CO_2 are generated per 2 moles of N_2 during production of ammonia from methane: $3CH_4 + 2N_2 + 3O_2 \rightarrow 4NH_3 + 3CO_2$. The shift to CO_2 is never complete, and CO and N_2O are also generated. The remaining CO_2 is generated by burning coal, gasoline, methane, propane, and diesel fuel.

[22] See the bottom row in Table I.

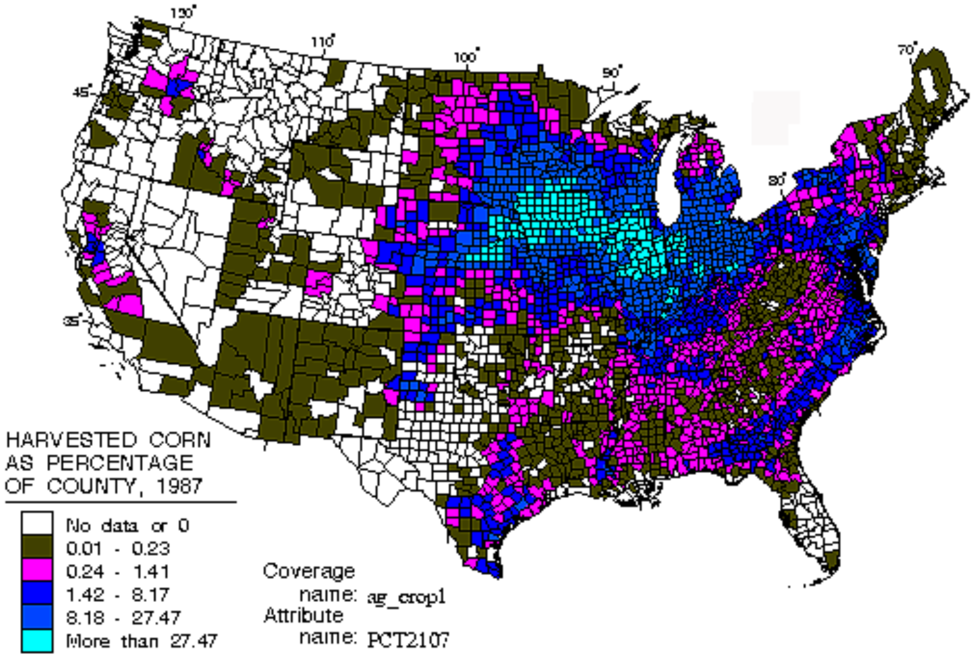

Figure 3. Fraction of county area used to grow corn in 1987. Source: U.S. Geological Survey, Water-Resources Investigations Report 94-4176, http://water.usgs.gov/-pubs/wri/wri944176/

taken into account. The complex issue of total gas emissions in the corn ethanol life-cycle deserves a separate, careful study.

Finally, one should consider the corn-related contamination of surface and ground water, which was disregarded in the Argonne report and the USDA reports. The bottom line is summarized in the map of groundwater contamination by nitrate, generated by the U.S. Geological Survey, and shown in Figure 2. This map demonstrates that the most contaminated states and counties are those that together grow 80% of the U.S. corn and produce 91% of ethanol: Illinois, Indiana, Iowa, Minnesota, Nebraska, Ohio, Michigan, South Dakota and Wisconsin (Shapouri et al., 2002), see Figure 3. The massive fertilizer run off and groundwater contamination related to industrial corn farming should be investigated separately, and their social costs factored into the energy costs of ethanol production.

Appendix C: Why include corn in the overall energy balance?

This Appendix was written in response to a brilliant message http://-groups.yahoo.com/group/energyresources/messages/37079, posted by Mr. David Delaney from Ottawa, Canada.

Mr. Delaney's key argument is: "The (Berkeley) paper treats the chemical energy of the corn as virtual gasoline. It includes this virtual gasoline as energy invested in the resulting ethanol. As a result, it always takes more energy in the form of actual plus virtual gasoline to create a quantity of ethanol than is contained in the ethanol. The paper concludes that this result shows that producing ethanol from corn wastes energy. [In this note I take no position with respect to the truth of the conclusion–it is the argument I am refuting.]..."

My answer to Mr. Delaney is as follows. Corn is *incipient* gasoline. Let us consider naturally growing corn that takes in only sun energy, precipitation as irrigation, and the aqueous natural fertilizers from soil. *Current* solar energy alone is not enough! Corn will not grow on concrete, or in bone-dry, nutrient-free sand. Therefore we always invest more into corn than mere solar energy. But water and the soil nutrients are accumulated at *different time scales* than the annual corn cycle. Therein lays the eventual demise of all plant-to-fossil-energy schemes, including Mr. Delaney's magic "ethanol plant," or corn.

Given enough time, tens of millions of years, and the right conditions, our corn *will* become crude oil (Hunt, 1996). Thus, nature will convert the corn free of charge to *more* of something more energetic than ethanol. Then our distant descendants might discover the converted corn, produce it, and refine to gasoline. This is the absolutely optimal outcome for the Earth, but not for us.

Our civilization does not have *time*. Instead, using the ancient solar energy in methane, coal and crude oil, we accelerate the incredibly *slow* natural processes of energy sequestration and conversion, and strive to obtain a human-made fossil fuel in annual cycles. But there is a price to pay. To make corn grow fast, we apply plenty of fertilizers, and use up a lot of energy in ways described so well by Prof. Pimentel and analyzed briefly in this paper. So we act irreversibly on a *time scale of human life*: we deplete soil and mine groundwater, and we also create an environmental mess: polluted rivers, aquifers, shallow seas, air, etc., which have their own restoration *time scales*, energy requirements, and costs.

At this point, I would like to point back to Appendix B and remind the Reader that the photosynthesis reaction can be written schematically as: Solar Energy + Water + $CO_2 \rightarrow$ Glucose + Oxygen. Since both the solar energy and CO_2 are "inexhaustible," it is the water (and the mineral nutrients dissolved in it, given appropriate soil) that limits the chemical energy accumulation in corn. From this point of view, the sun acts as a chemical *catalyst*, it facilitates the accumulation, but remains unchanged by it. Therefore, inclusion of the calorific value of corn kernels in the energy inputs of the corn-to-ethanol cycle serves a useful purpose.

I do not want the Reader to leave with an impression that other fossil energy generation schemes, most notably the recovery and processing of crude oil and natural gas, are free of conversion inefficiencies. When these inefficiencies are taken into account, the net energy in gasoline, calculated by us as 116,000 Btu/gallon will decrease, sometimes dramatically. For example, all oil recovery schemes which "melt" heavy crude oil with steam generated by burning fossil fuels, will also suffer from an unfavorable net energy[23] balance. It is well known that most of the potentially recoverable oil in the Western Hemisphere, in Venezuela, Canada and the U.S., is locked in the heavy and ultra-heavy (tar) crude oil deposits.

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[23] Net energy analysis seeks to compare the amount of energy delivered to society by a technology to the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a socially useful form.

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