Energy Analysis of the Corn-Ethanol Biofuel Cycle

First Draft

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1 Introduction

The combination of the appearance of professional respect for scientific rigor and the contempt for thorough but tedious science is toxic (Jacobs, 2004), a poison that infects many activities in the U.S.: foreign aid programs, teaching, medical drugs and fads, nutrition and other lifestyle advice, energy policy, and agricultural policies – just to name a few.

Following its Galilean and Newtonian roots, science has also made little progress in dealing with complex systems; particularly in biology and ecology it tends to become arrested at the stage of investigating small isolated parts, with little grasp of how these interact with other parts of integrated systems (Capra, 1996; Odum, 1998; Jacobs, 2004; Patzek, 2004).

After several decades of research, the American public may legitimately ask: Why do the various energy balances of the corn-ethanol cycle still differ so much? Why do some authors claim that the corn-ethanol cycle has a positive net energy balance (Wang et al., 1997) and (Shapouri et al., 2002), while others claim the opposite (Pimentel, 2003) and (Patzek, 2004)?

The main reasons for the often contradictory conclusions of different researchers can be ranked in increasing importance as follows:

Human Error. For example, the USDA estimate (Shapouri et al., 2002) of efficiency of corn conversion to ethanol in wet milling plants, 2.68 gal/bushel, is equal to the mean value reported in the Corn Chemistry and Technology Handbook (White and Johnson, 2003), page 709, for dry corn. This estimate has been applied to wet corn grain with 15% moisture, rather than to the moisture-free dry grain. This error overestimates the cycle energy output by 15%. Pimentel's (2003) estimate of energy spent on producing nitrogen fertilizer was based on an obsolete technology and was 30% too high. Patzek's (2004) efficiency of conversion of corn to ethanol was too low by 11% because he did not account for starch hydration. These discrepancies are easy to understand and have been reconciled, see Patzek (2004), Part I.

Externalization. For some, the environment is an inert, ever-lasting substrate from which one derives financial benefits without regard to what is done to the soil, air, surface and ground water, and the irrevocably depleted natural resources. For others, damage done to the environment and resource depletion are important, and are included in their analyses. Different degrees of externalization result in different system boundaries and energy fluxes that cross them. For example, USDA (2002) subtracts 33% from the fossil energy spent on distilling the ethanol (the single largest energy outlay of the cycle) claiming that the distiller's dry grain & solubles (DDGS), a by-product of starch separation before fermentation and distillation, mixed with mostly dead yeast leftovers, is a cattle feed. Patzek (2004) observes that these byproducts should be returned to corn fields to replenish the vital nutrients, diminish the significant dependence of the the corn-ethanol cycle on fossil fuels, and help in preserving soil structure. Consequently, Patzek does not allow for the DDGS energy credit. The uncorrected USDA mistake described above and their robust energy credit explain most of the discrepancies in the respective net energy balances of the corn-ethanol cycle, see Part I in (Patzek, 2004) for an in-depth discussion. Then there are even more fundamental differences in approach.

Different Questions. Given today's seemingly abundant agricultural land with plenty of clean water and air, readily available fossil fuels, minerals and metals, and a rich industrial infrastructure (machinery, transportation, etc.), some (Wang et al., 1997; Shapouri et al., 2002) may ask: How much "renewable" fossil energy can be produced per unit area of an industrial corn field in a process driven by all of these resources? Having answered this question, they then tacitly assume that the same high energy yield will be maintained every year for many decades to come. Others observe that the fossil energy consumed in the U.S. as motor gasoline (18 EJ/year in 2003) is 18 times greater than the energy required to feed the U.S. population. Consequently, no agricultural crop can sequester enough solar energy to quench the current thirst for gasoline (Patzek, 2004), regardless of the extraordinary financial and environmental costs of converting the spurious subsidized food into fuels. So they ask: How could solar energy be converted into useful work more efficiently than by growing corn, converting the corn grain to ethanol, and burning this ethanol in a car engine or fuel cell? Then there are those who note that converting all U.S. corn into ethanol would satisfy 1/10th of the *unchanged* gasoline consumption, while doubling the average efficiency of the U.S. car fleet would cut this consumption by 1/2 *and* decrease fossil fuel consumption by industrial agriculture and ethanol refineries (Pimentel et al., 2004; Patzek and Pimentel, 2005).

Influence of Money. Between 1995 and 2003 USDA distributed $131 billions in farm subsidies. Recipients of payments made through most cooperatives – and the amounts – have not been made public. $104 billions went to commodity subsidies, $16 billions to conservation, and $11 billions to disaster relief (Source: Farm Subsidy Database, http://www.ewg.org/farm, accessed July 2, 2005). Corn subsidies were $37.4 billions,

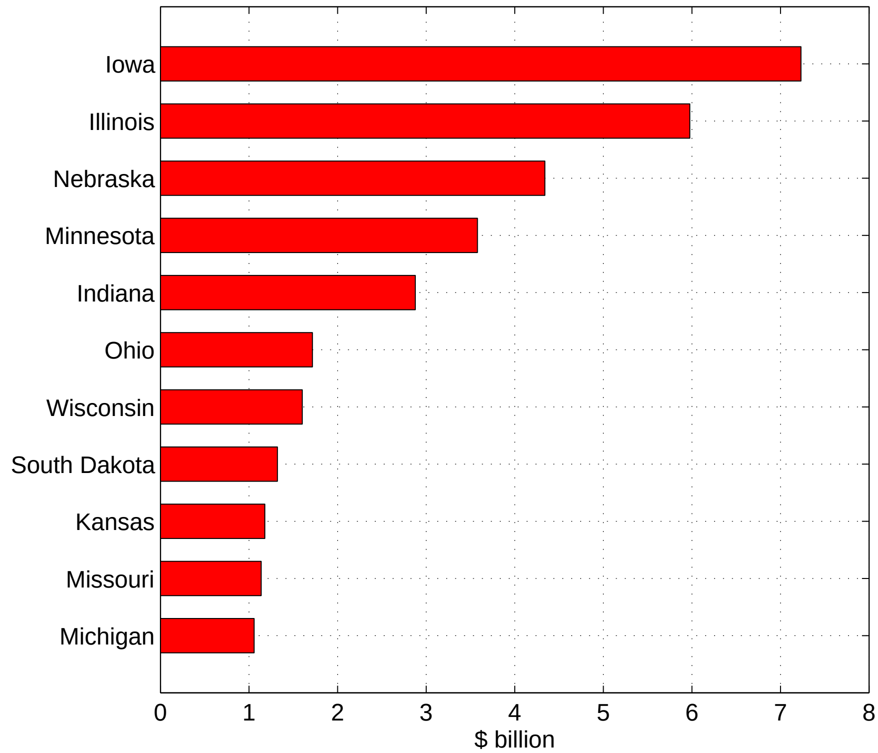

Figure 1: Largest corn subsidies by state, 1995-2003.

or ∼\$2 – \$7 billions per year, see **Figure 1**. From 1995 to 2003, the top 10 percent of corn subsidy recipients were paid 68 percent of all corn subsidies. The mean payments were \$465 172 each for the top first percent, and \$176 415 each for the top tenth percent of recipients. The bottom 80% of farmers received mean payments of \$4763 each. According to the Center for Responsive Politics (http://www.opensecrets.org/, accessed July 2, 2005), between 1990 and 2005, Agribusiness paid \$356 millions to elected officials, 31% to Democrats and 69% to Republicans[1]. Individuals donated \$135 millions. The peak donations occurred in the 2000 and 2002 election cycles, exceeding 59 and 54 million dollars, respectively. In 1999 and 2000, farm subsidies peaked at \$7.2 and \$7.7 billion, respectively. The 2004 election cycle donations exceeded 53 million dollars, vs. \$25 millions from the Oil&Gas Sector. In 2004, on the average, *all* U.S. congressmen received \$44 thousands each in Agribusiness donations, and 70 senators received \$79 thousands each; the top 18 recipients in the House and Senate received between \$689 and \$249 thousands each[2].

With so much public money subsidizing the production of plant food no one needs, it is not surprising that we end up burning this food as automotive fuels[3] at an additional

[1]Over the same time period, the Oil&Gas Sector gave \$182 million dollars, 25% to Democrats and 75% to Republicans.

[2]The top 18 recipients of the 2004 Oil&Gas Sector donations received between \$276 and \$126 thousands each.

[3]"Ethanol production makes huge amounts of the nation's corn disappear – some 1.4 billion bushels went into ethanol production in 2004 – and that affects overall corn supply and helps shore up corn prices nation-

cost to the society and environment, see Patzek (2004), Part IV. One may conclude that the USDA-sponsored research on corn-ethanol ought to be reviewed by GAO. I would gladly submit my biofuels research to the simultaneous review.

Because burning corn ethanol is expensive, the U.S. subsidizes it with the $0.51/gal gasoline tax subsidy, the $0.10/gal small ethanol producers tax credit, and further grants and loan assistance available through USDA. State tax credits vary significantly, but average about $0.15/gal, see **Figure 2**.

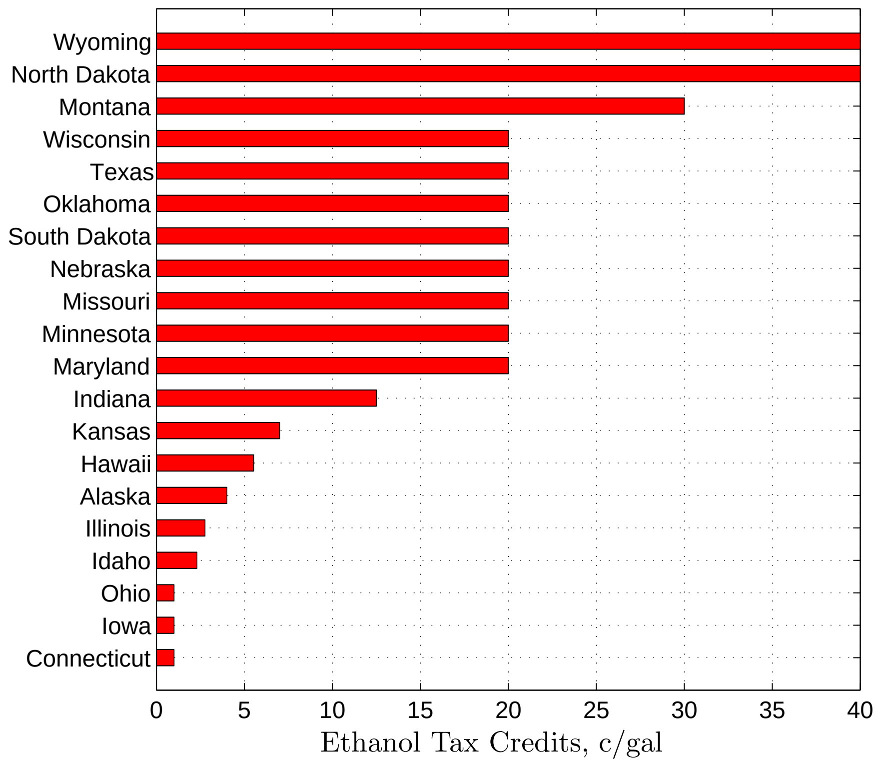

Figure 2: Ethanol tax credits by state. Source: National Conference of State Legislatures, http://www.ncsl.org/programs/energy/ethinc.htm, accessed July 2, 2005. In addition, Montana provides an incentive of $2 million per ethanol plant per year and producer.

Different initial questions lead to different chains of the followup questions and observations. Here it is noted that the major competing devices that also sequester solar energy, wind turbines and photovoltaic cells, output electricity which is readily converted to shaft work by electric motors with efficiency of 80–97% (DOE, 2005), depending on the load and motor power. The output of an ethanol refinery is a fossil fuel that is converted to shaft work with efficiency of 20-40%, depending on engine design. Since the fossil fuels from biomass are used mostly to turn wheels in cars and trucks, their ability to generate electricity (Patzek, 2004; Patzek and Pimentel, 2005) — not their heats of combustion — should be used in consistent comparisons with other means of sequestering solar energy. It will be shown here

wide." National Corn Growers Association, http://www.ncga.com/ethanol/main/economics.htm, accessed July 2, 2005.

that per unit area of land even a mediocre photovoltaic panel produces about 100 times more power than corn ethanol burned in an average car engine.

2 Preliminaries

Here the term *Energy Analysis* describes the evaluation of the energy, free energy, availability (exergy), or any other thermodynamic quantity sequestered in the production of the anhydrous ethanol derived from corn grain. *Sequestered* means *set apart*, to indicate that energy is tied up in the ethanol biofuel and the process byproducts, in addition to the energy used to drive the entire production process.

The Gibbs free energy referenced to the environmental conditions (P_{atm}, T_{atm}), otherwise known as availability or exergy, will be used for reporting the data.

For a fuel, its heating value measured at constant atmospheric pressure, or enthalpy of combustion, will be referenced to the gaseous CO_2 and liquid H_2O. This enthalpy is called the *gross* or *high* heating value (HHV) of the fuel.

The fundamental unit of energy will 1 joule (J) and powers of ten thereof. The specific energies will be expressed in joules per kilogram (J/kg). The fluxes will be reported in W/m^2.

2.1 The System and Levels of Analysis

The system is the portion of the universe chosen for study. The system is defined by specifying its boundary and the flows of mass and energy that cross this boundary. Energy analysis often begins with a focus on a product (ethanol) and the process stage (refining) by which it is fabricated from material inputs (corn grain, air, water, and fossil energy). The system boundary can be defined so as to obtain this process stage and none other, and the energy analysis then calculates how much energy is required to obtain this single step. But the system could instead be defined to account for the energy used to prepare material inputs that are themselves fabricated in prior stages (fossil fuels, transportation, and agriculture). The latter approach is chosen here. Another choice of the system boundary would also include the final process stage (electricity generation) and the processes that generate the inputs to the final stage. Again, this is the choice made in the current analysis. Finally, recycling of the system waste streams could be accounted for. Here only corn stalk, refinery byproducts, and waste water are recycled.

As defined here, the corn-ethanol production system consists of three subsystems in series, see **Figure 3**. The first subsystem is industrial agriculture, which uses good quality soil, water, air, solar energy, seeds, fossil fuels and fossil-fuel derived chemicals, earth minerals, electricity, machinery and infrastructure, and transportation, to produce corn grain, chemical wastes in soil, water and air, as well as soil erosion, and some grain losses. The second subsystem is ethanol refineries. It takes in the net corn grain produced in Subsystem 1, fossil fuels, air, water, yeast and enzymes, transport and machinery, and outputs anhydrous ethanol, byproducts (gluten feed and meal, or dried distillers grain solubles (DDGS)), and chemical wastes. The third subsystem is machines that convert the ethanol into shaft work or its portable equivalent, electricity. The inputs to the last subsystem are the net anhydrous

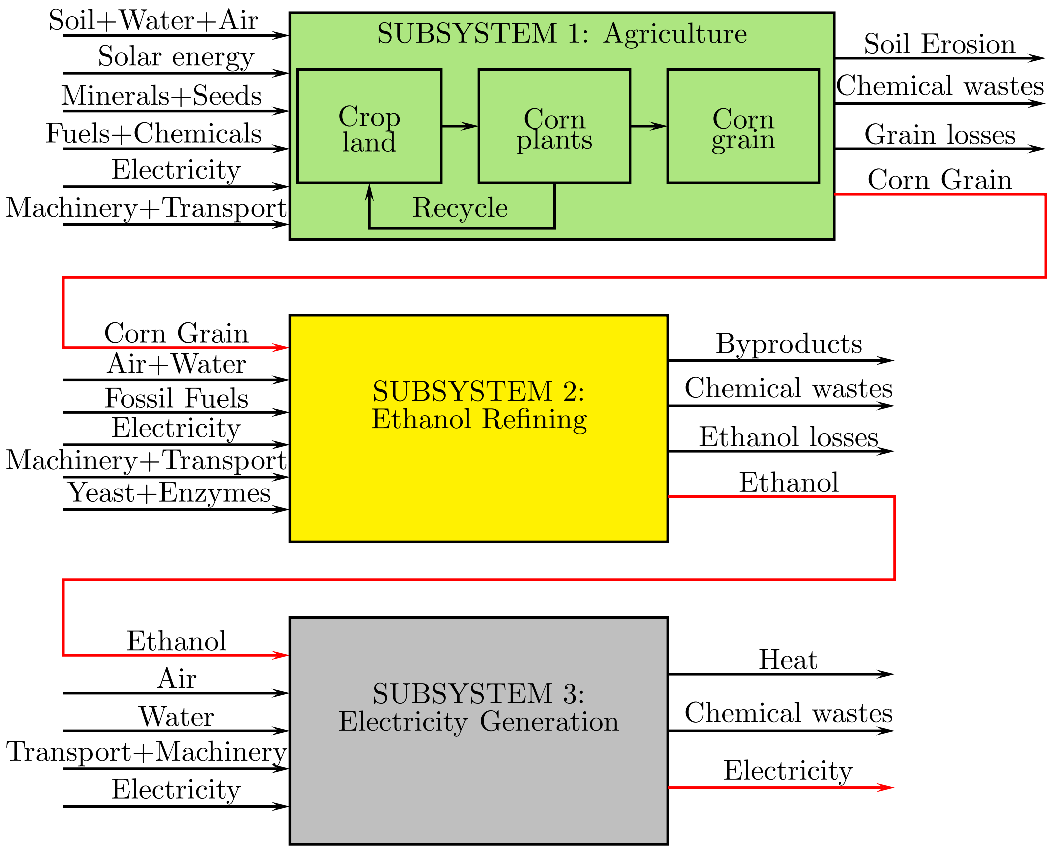

Figure 3: The corn→ethanol→electricity system consists of three subsystems in series. In these subsystems, the energy costs of labor have been omitted. The low-quality heat generated in Subsystems 1 and 2 has also been neglected. It is assumed that corn stalk is decomposed and recycled to improve soil structure. The DDGS byproduct output of Subsystem 2, and the CO_2 produced in Subsystems 1–3, become inputs to Subsystem 1, thus creating an incomplete carbon cycle, and partially recycling other nutrients. The contaminated water outputs can also become inputs after purification, creating a partial water cycle.

ethanol, electricity (some of which may be recycled internally, thus lowering the conversion efficiency), machinery and transportation. The outputs are electricity, chemical wastes and large quantities of heat, which may or may not be further utilized. The DDGS output of Subsystem 2 is an input to Subsystem 1, thus creating a partial nutrient and carbon cycle. A fraction of the CO_2 outputs by Subsystems 1-3 is an input to Subsystem 1, thus supplementing the carbon cycle.

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NRR	Exergy	CExC	Units	Comments
Corn	18.0	5.4	MJ/kg dry	U.S. Industrial Agriculture
Ammonium Nitrate	10.5	99.6	MJ/kgN	30-years old technology
Phosphate	0.10	16.8	MJ/kg P_2O_5	H_2SO_4 CExC
KCl	0.26	12.9	MJ/kg KCl	Sylvinite ore, 1:1 K:Na
Lime	1.97	10.0	MJ/kg CaO	Calcinated limestone
Herbicides	261.0	300.1	MJ/kg	1.15 exergy
Seeds	103.8	119.4	MJ/kg	1.15 exergy
Electricity	3.6	11.8	MJ/kWh	Plant eff. of 34.6%
Diesel	44.4	53.2	MJ/kg	Typical value
Gasoline	45.6	54.4	MJ/kg	Mean value
Natural Gas	46.40	52.9	MJ/kg	Typical value
LPG	48.9	61.60	MJ/kg	Authothermic cracking
Steel	7.1	59.3	MJ/kg	Mean value from ore in the ground

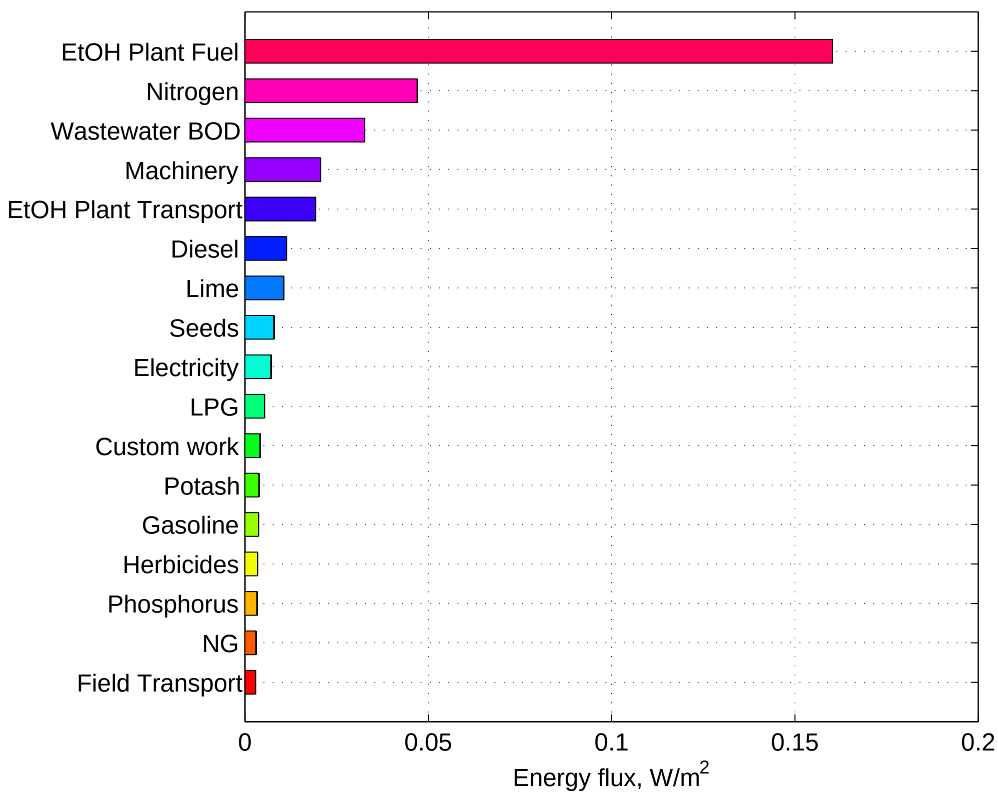

Figure 4: The cumulative exergy consumption (CExC) in corn-ethanol production.

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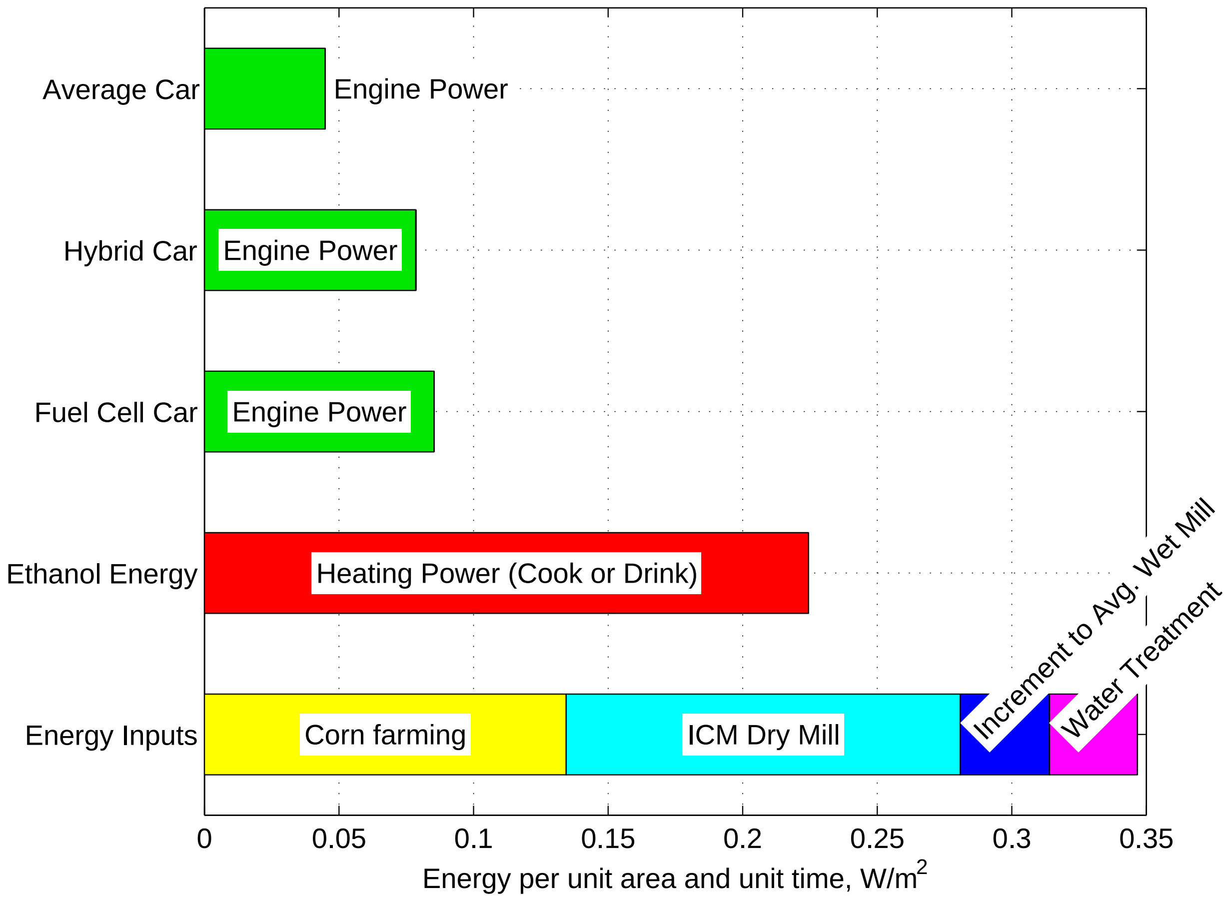

Figure 5: This chart illustrates my calculation of energy fluxes in the corn-ethanol cycle. The green bars illustrate engine power in different cars using corn ethanol from 1 m^2 of cornfield as fuel. The red bar is the energy one would get if one drank this ethanol and metabolized it, or burned it in a stove. Fossil fuels and environmental resources are depleted in corn farming (the yellow segment), and in subsequent production of corn ethanol in the best dry mill today (the light-blue segment), as advertised by ICM, Inc. Wet mills use somewhat more energy and more water, as illustrated in the dark blue and magenta segments, but also deliver a large variety of byproducts. It takes about seven times more energy to produce ethanol than ethanol can deliver as work to power an average passenger car. Hybrid and fuel cell engines are more efficient than the average passenger car, but it still takes about four times more energy to produce ethanol than the mechanical work this ethanol delivers. A 20 mpg gasoline truck driven only 10,000 miles per year consumes the equivalent of 102 gigajoules (GJ) per year, or 3,240 watts (W) of free energy as fuel. From this chart it follows that if this truck were using ethanol fuel, it would need an equivalent of 8.8 acres of cornfield: To consume the same 3,240 W of free energy as ethanol, the truck would require approximately 3.6 acres of cornfield. But it would also consume 5,000 W of free energy to recover some of the fossil energy used, and "undo" some of the environmental damage caused by the production of corn ethanol. These 5,000 W of free energy might be produced from an equivalent of 5.2 acres of cornfield. In contrast, an average wind turbine generates about 1 W per square meter (W/m^2) of electricity, which can be converted to mechanical work with 85 - 95 percent efficiency. A photovoltaic cell generates 10 - 20 W/m^2 of electricity. Thus, wind turbines and solar cells are 20 and 100 times more efficient in delivering mechanical work than corn ethanol.