Total Energy Analysis

Corn Ethanol Production

Prepared as an assignment for a Guided reading course on **Energy sources and Materials research** given by **Prof. David Cahen, Prof. Ronny Neumann**. Feinberg Graduate School, Spring 2008.

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Main References

1. R. Hammerschlag, 2006. Ethanol's energy return on investment: A survey of the literature 1990-present. *Environ. Sci. Technol. 40, 1744-1750.*
2. H. shapouri, 2002. The 2001 net energy balance of corn-ethanol. *U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses. Agricultural Economic Report No. 813.*
3. D.Pimentel and T.Patzek, 2005. Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower. *Natural Resources Research, Vol. 14, No. 1,* DOI: 10.1007/s11053-005-4679-8.
4. T.W. Patzek, 2004. Thermodynamics of the Corn-Ethanol Biofuel Cycle. *Critical Reviews in Plant Sciences, 23, 6, 519-567 (web version updated in 2006).*

Lecture outlines

- Introduction
- Corn ethanol production:
  - Total energy analysis:
    - General: choosing units, HHV vs. LHV
    - four production stages and their energy input parameters
    - Positive vs. negative scenarios: why do they differ?
    - A complete energy analysis for the most energy consuming stages
    - Co-products
    - Our point of view and an open discussion
  - Accounting for the environmental impacts
    - Sustainability
    - The concept of exergy
    - Is corn-to-ethanol sustainable?
    - CO_2 emission
    - Water in the corn-to-ethanol process
  - Summary
- Small surprise

Introduction

- The “running out of fuel” problem
- Many solutions, but are they beneficial?
- We will discuss corn ethanol - motivation
- In the current literature of bio-fuel: Lots of parameters, in different units and scales leads different authors to different conclusions ➔ order should be made!
- Our goal: make an order in the mess and come up with an objective answer

Corn ethanol – basic assumptions I

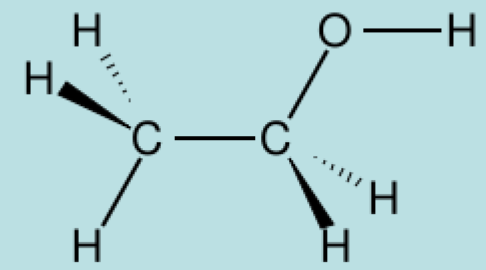
LHV: $C_2H_5OH(g) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(g)$ ΔH = 76,000 BTU/Gallons
HHV: $C_2H_5OH(g) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$ ΔH = 84,681 BTU/Gallons

Since in all existing engines the water is vaporized, all numbers in this presentation are normalized to the Lower Heating Value (LHV).

Remark: there is no debate over the LHV value
(±360 BTU/Gallons - at least that ☺)

Comparison is based on energy (and not on volume) -
Gallon of ethanol has less energy than gallon of gasoline:

LHV (gasoline): 112,300 BTU/Gallons
HHV (gasoline): 121,500 BTU/Gallons

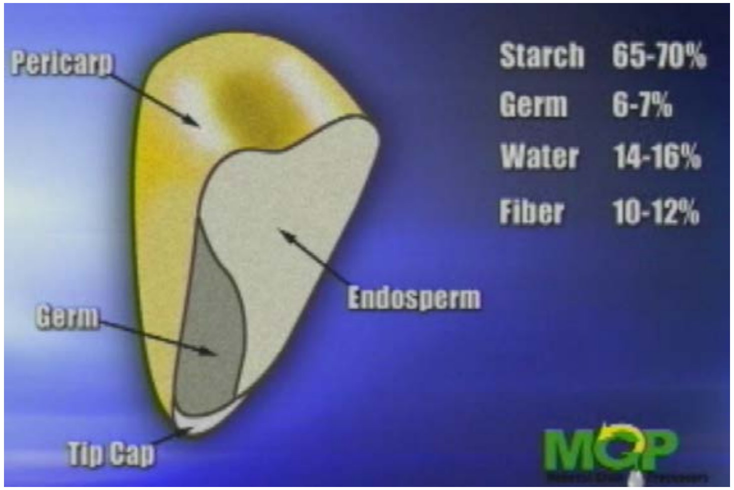


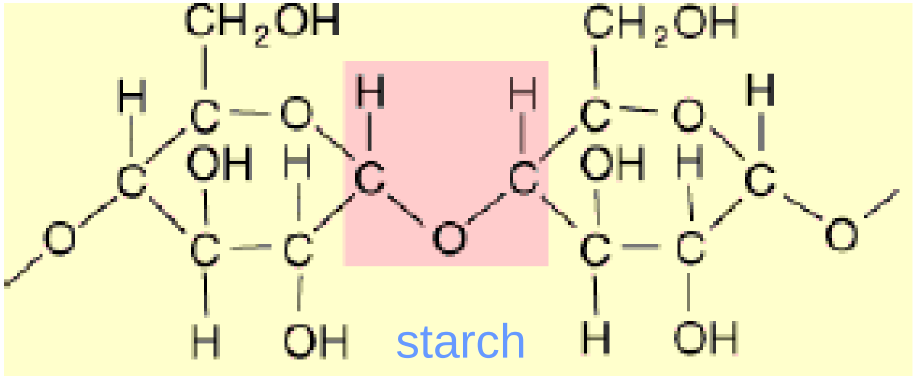
Ethanol: C_2H_5OH

Here, all units are converted to:
Volume – Gallons (1 Gallon = 3.78 Liters)
Energy – BTU (1 BTU = 1055.05 Joules)

Corn ethanol – basic assumptions II

- Here we consider only starch ethanol
- The starch composes ~66% of the corn grain mass





Definition: $r_E = \frac{r_{out}}{r_{in,\ nonrenewable}}$ → Note the dependency over the choice of HHV vs. LHV

If r_E (ethanol) > 1 ➔ ethanol production is energetically beneficial

The main 4 stages in corn ethanol production

E10 = 10% ethanol
E85= 85% ethanol

1 corn production → **2** corn transportation → **3** ethanol conversion → **4** ethanol distribution

1 corn production

- Seeds
- Fertilizers:
  - Nitrogen
  - Phosphorus
  - Potassium
  - Lime
- Herbicides
- Insecticides
- Irrigation

2 corn transportation

- Fuel

3 ethanol conversion

- Starch to glucose
- Fermentation
- Distillation
- Filtration
- Dehydration

4 ethanol distribution

- Fuel

The main 4 stages in corn ethanol production (in BTU/Gallons)

Stage	positive (green)	negative (red)
1 corn production	18,875	37,830
+ 2 corn transportation	2,138	4,830
+ 3 ethanol conversion	47,116	56,355
+ 4 ethanol distribution	1,487	4,965
= total	69,616	103,980
- "Co-products"	26,250	6,680
= $r_{in, nonrenewable}$	43,366	97,300

LHV = 76,000 (≡ r_{out})

$$r_E = \frac{r_{out}}{r_{in,\ nonrenewable}}$$

positive estimation: r_E = 1.75

negative estimation: r_E =0.78

what makes the difference?

- different parameters
- different data

Shapouri

Pimentel et al.

What makes the difference?

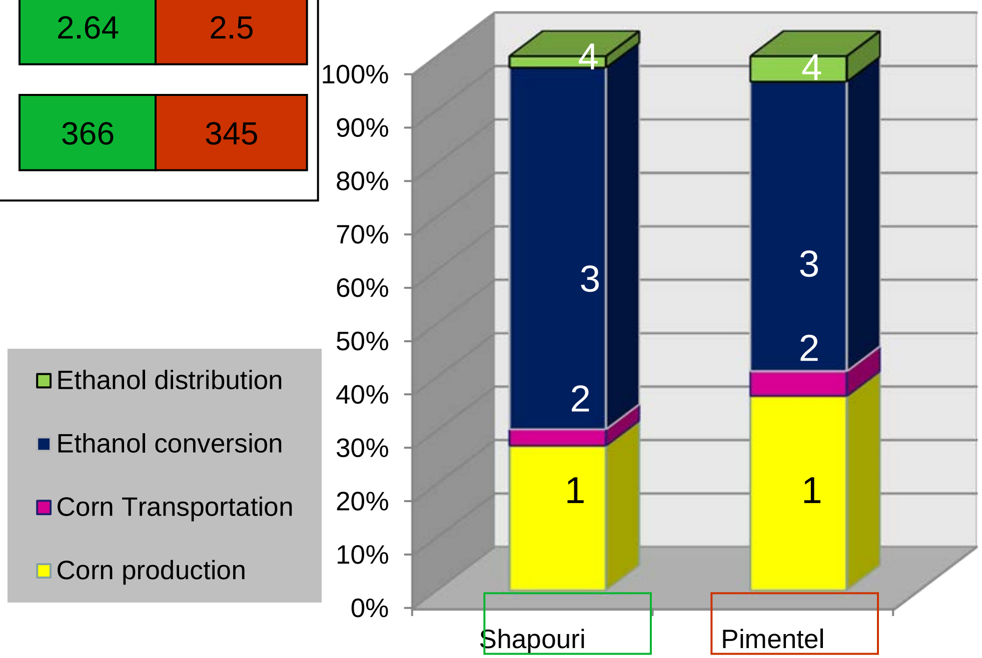
$r_E = 1.75$	$r_E = 0.78$

	1 corn production	+	2 corn transportation	+	3 ethanol conversion	+	4 ethanol distribution	=	total
$r_E = 1.75$	18,875	+	2,138	+	47,116	+	1,487	=	69,616
$r_E = 0.78$	37,830	+	4,830	+	56,355	+	4,965	=	103,980

	total	- "Co-products"	= $r_{in, nonrenewable}$
$r_E = 1.75$	69,616	26,250	43,366
$r_E = 0.78$	103,980	6,680	97,300

Ethanol yield?

	$r_E = 1.75$	$r_E = 0.78$
Bushels of corn / acre	139	138
Gallons of ethanol/ bushels of corn	2.64	2.5
Gallon of ethanol/ acre	366	345



Next, we'll consider in detail the most two energy consuming stages

Corn production 18,875 37,860 – other parameters

Input	Pimentel	Shapouri	Difference
	Btu per Gallon of ethanol from corn production		
Labour	2155	---	-2155
Machinery	4749	---	-4749
Diesel	4679	2828	-1851
Gasoline	1890	1323	-567
Nitrogen	11421	8924	-2497
Phosphorus	1260	613	-647
Potassium	1171	726	-445
Lime	1470	24	-1446
Seeds	2426	227	-2199
Irrigation	1493	62	-1431
Herbicides	2893	1155	-1738
Insecticides	1306		-1306
Electricity	159	839	680
Transport	788	76	-712
Liquid Petroleum Gas	---	790	790
Natural gas	---	694	694
Custom work	---	594	594
Total	37860	18875	-18985

highest parameter difference

highest data difference

Nitrogen Fertilizer

18,875	37,860

Converting Natural Gas to Ammonia

Nitrogen Fertilizer – consumption and energy use in Production

Fertilizer type	Ton N (Consumption)	%	Btu/lb of N (LHV)
Ammonia	4,172,780	46.24	20548
Aqueous Ammonia (22% ammonia, 65% ammonium nitrate)	137,781	1.53	22096
Ammonium Nitrate	645,450	7.15	22162
Ammonium Sulfate	173,837	1.93	17872
32% Nitrogen Solution (34.2% Urea, 45.8% Am nitrate, 20% water)	2,309,709	25.59	23003
Urea	1,584,572	17.56	NR
Total	9,024,129	100%	--

Graboski (2002)

	Shapouri	Pimentel
Amount (lb of N/ac)	134	136
Energy to produce (Btu/lb of N)	24500	28900
Energy cost (Btu/Gal. Of ethanol produced)	8924	11421

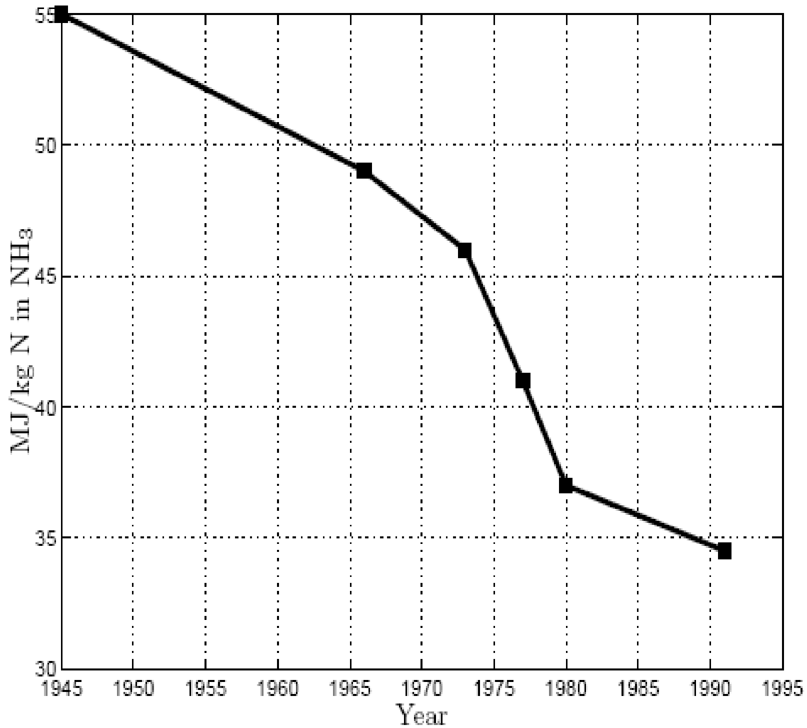
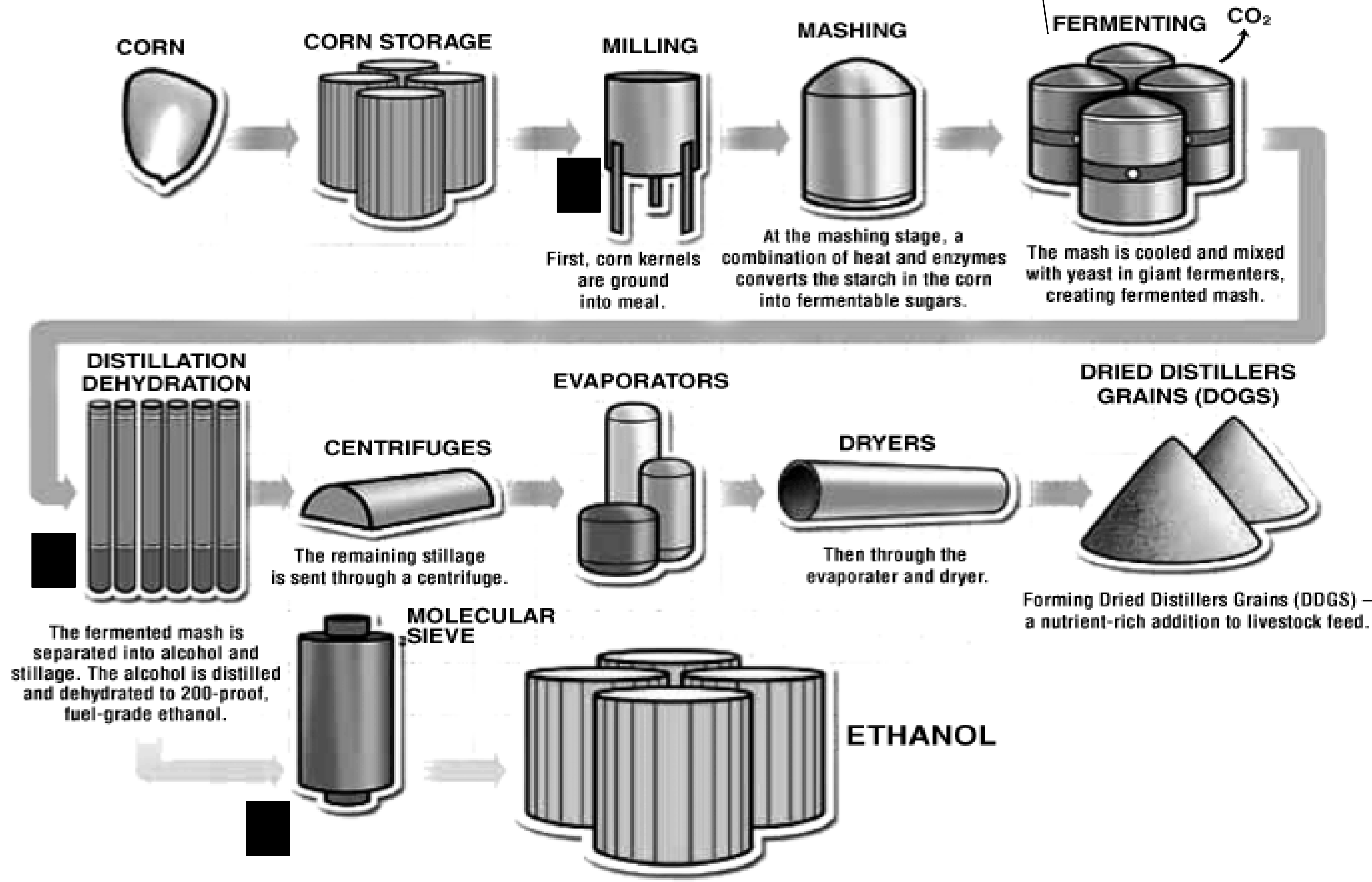


Figure 3: History of energy efficiency of ammonia production in MJ/kg N. Source: G. Kongshaug (1998).

Ethanol conversion – dry milling

47,116	56,399

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



Ethanol conversion – parameter comparison

highest parameter difference

highest data difference

Input	Pimentel	Shapouri	Difference
	Btu per Gallon of ethanol produced		
electricity	15165	12416	-2749
Steam/Thermal	38190	34700	-3490
Water	1350	---	-1350
Stainless steel	180	---	-180
Steel	180		-180
Cement	120	---	-120
95% to 99.5%	135		-135
Sewage effluent	1035	---	-1035
Total	56355	47116	-9239

Co products | 26,250 | 6,680 | – how are they assessed?

1
"Output weight basis"
Translating "food nutritional calories" to BTU – ~40%

DDGs

2
"Replacement value "
Energy credit are assumed to be equal to the energy required to produce a substitute for the ethanol co product – ~19%

3
"None"
0%

| 30% | 6% |

"Replacement value" – using soybeans

What do you think?

So, is ethanol production energetically efficient?

	Pimentel	Shapuori
Corn production	35363	23624
Corn transportation	4830	2138
Ethanol conversion	56355	49501
Ethanol Distribution	4965	1487
Total Exluding co-products	101513 (103980)	76750 (69616)
$r_{in,\ nonrenewable}$	94833	70070

LHV = 76,000 ($\equiv r_{out}$)

$$r_E = \frac{r_{out}}{r_{in,\ nonrenewable}}$$

r_E (gasoline) = 0.76

r_E >0.76 → ethanol production consume less non-renewable energy in its manufacture than gasoline

	Shapuori	Pimentel
Case 1: No Co-products	positive estimation: r_E = 0.99	negative estimation: r_E =0.75
Case 2: Co-products (Pimentel)	positive estimation: r_E = 1.08	negative estimation: r_E =0.8

Question: What if ethanol will be used in the process instead of gasoline?

But, there is more to consider…

- Thermodynamics
- Economy of scale
- Environmental issues
- Economical, ethical and political considerations

Corn-to-ethanol and Sustainability

- What is sustainability and why do we care?
- The concepts of Exergy and CExC
- Restoration work W_R
- A total **exergy** analysis of the corn-to-ethanol process
- Emphasis on CO_2 emission
- Emphasis on the water cycle

(according to the Patzek-Pimentel group)

Sustainability

A cyclic process is sustainable iff:

1. It is capable of being **maintained without interruption**, weakening or loss of quality “forever”, AND
2. The **environment** on which this process feeds and to which it expels its waste **is also sustained** “forever”.

Why do we want sustainability?

“Meeting the needs of the present without compromising the ability of future generations to meet their own needs”.

In other wards…

We want solutions that will be efficient in the long-term and will cause minimal damage to our society.

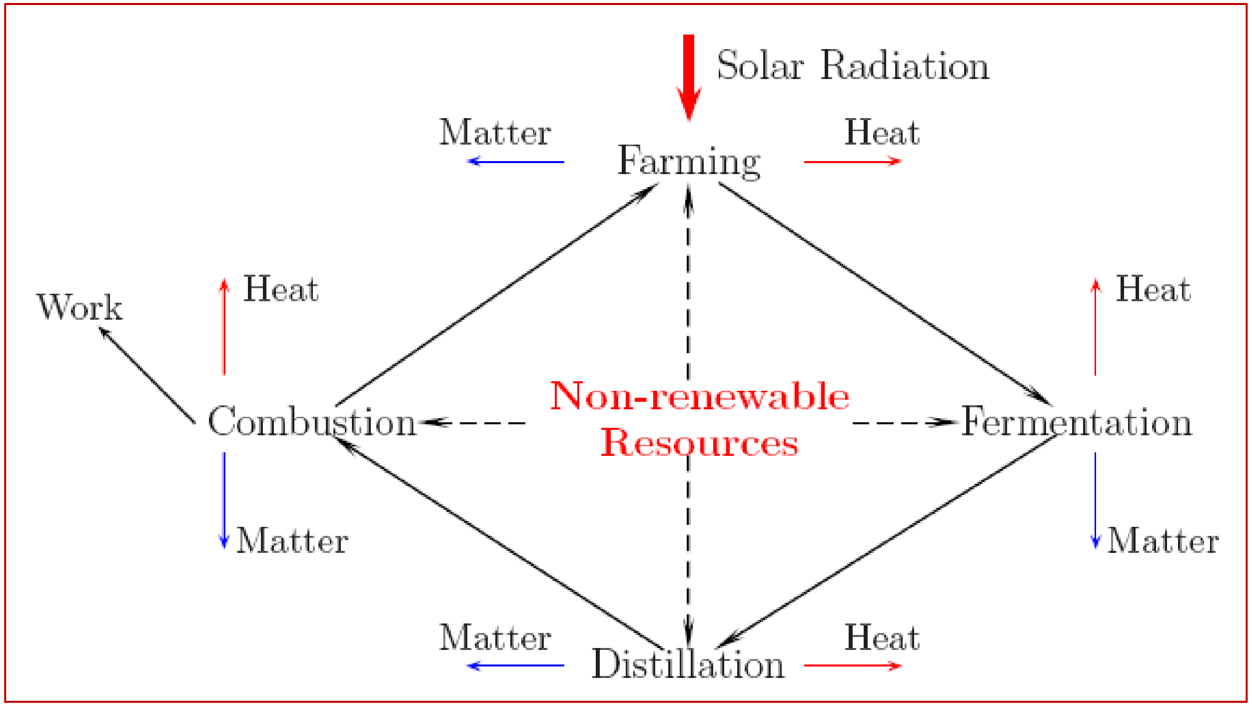
Exergy analysis - A tool for sustainability evaluation

Exergy Analysis: a concept that uses conservation of mass and energy principles together with the 2nd law of thermodynamics for analysis and improvement of energy (and other) systems.

Various ways to look at exergy:

1. Exergy consumption during a process is proportional to the **entropy** created due to **irreversibility** associated with the process.
2. Exergy is a measure of the **potential** of a system **to cause change** as a consequence of not being completely in stable equilibrium relative to the reference environment.

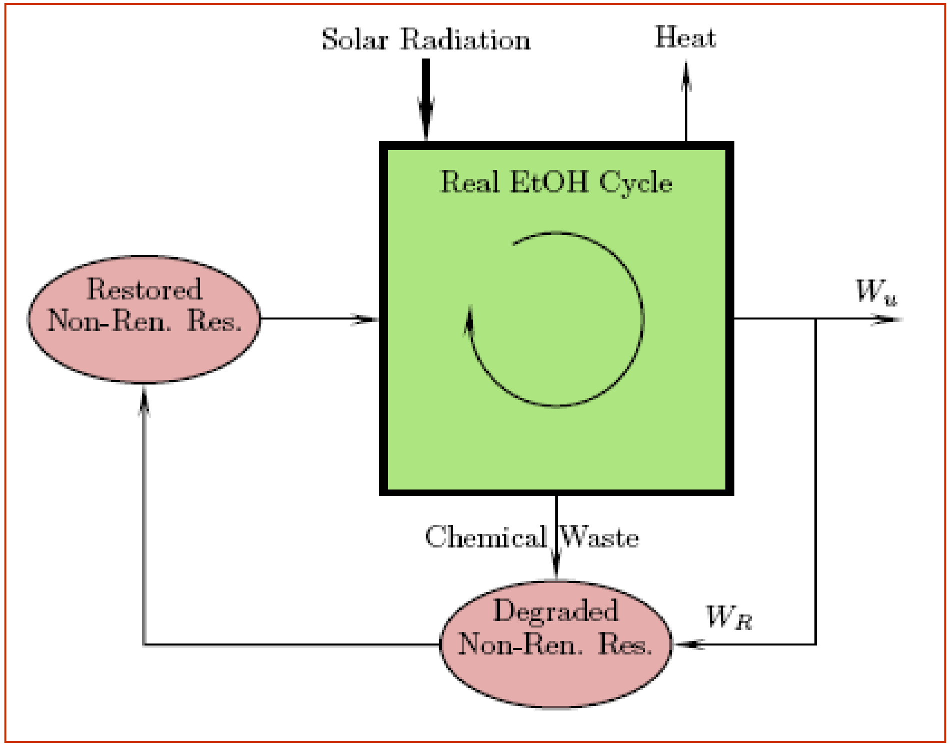
The real corn-ethanol cycle



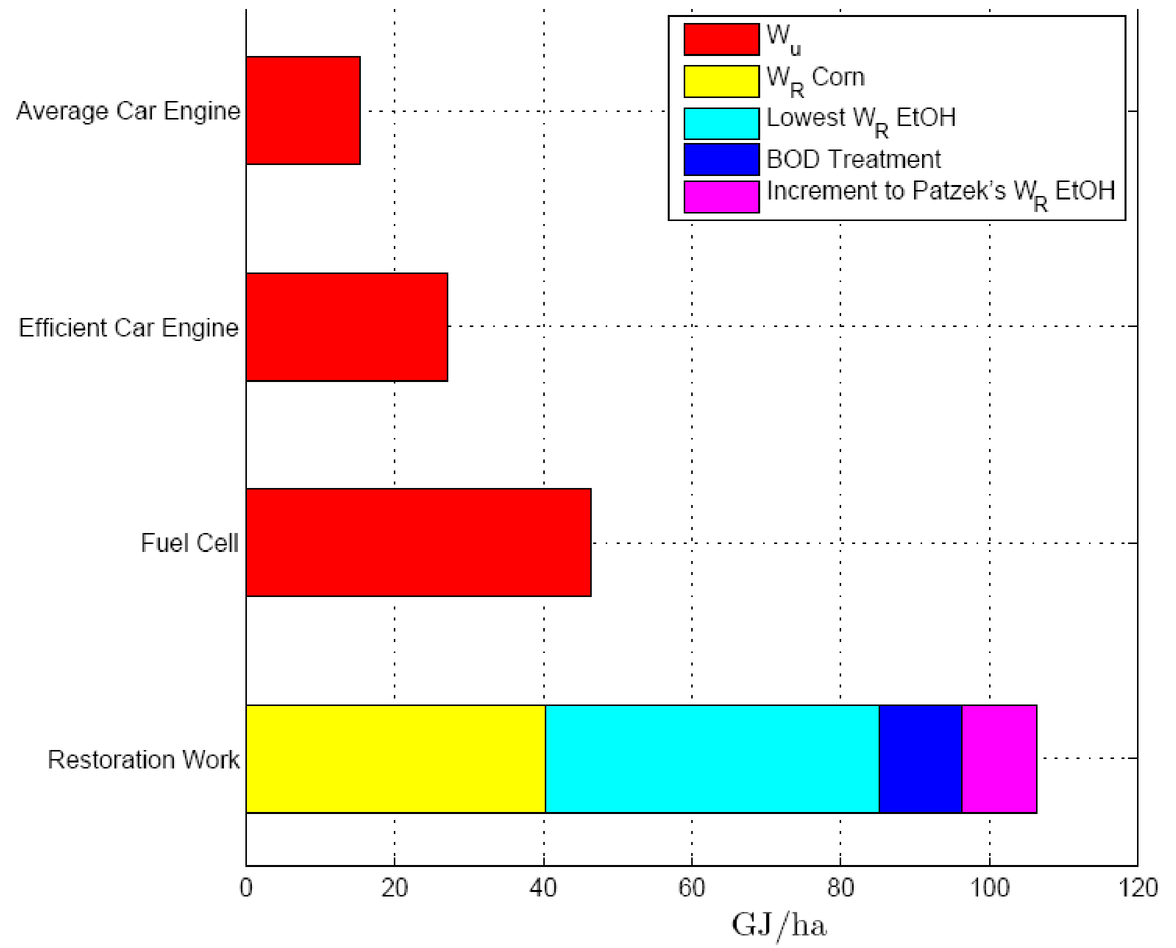
The **real-industrial cycle** is

- Driven by solar energy and non-renewable resources: crude oil, methane, coal, electricity (from fossil fuels), earth minerals, soil nutrients, groundwater
- Outputs are heat, O_2, CO_2, CO, NH_3, NO_X, SO_X, CH_4, water (liquid and vapor), contaminants of soil, water and air.

Is corn-to-ethanol process sustainable?



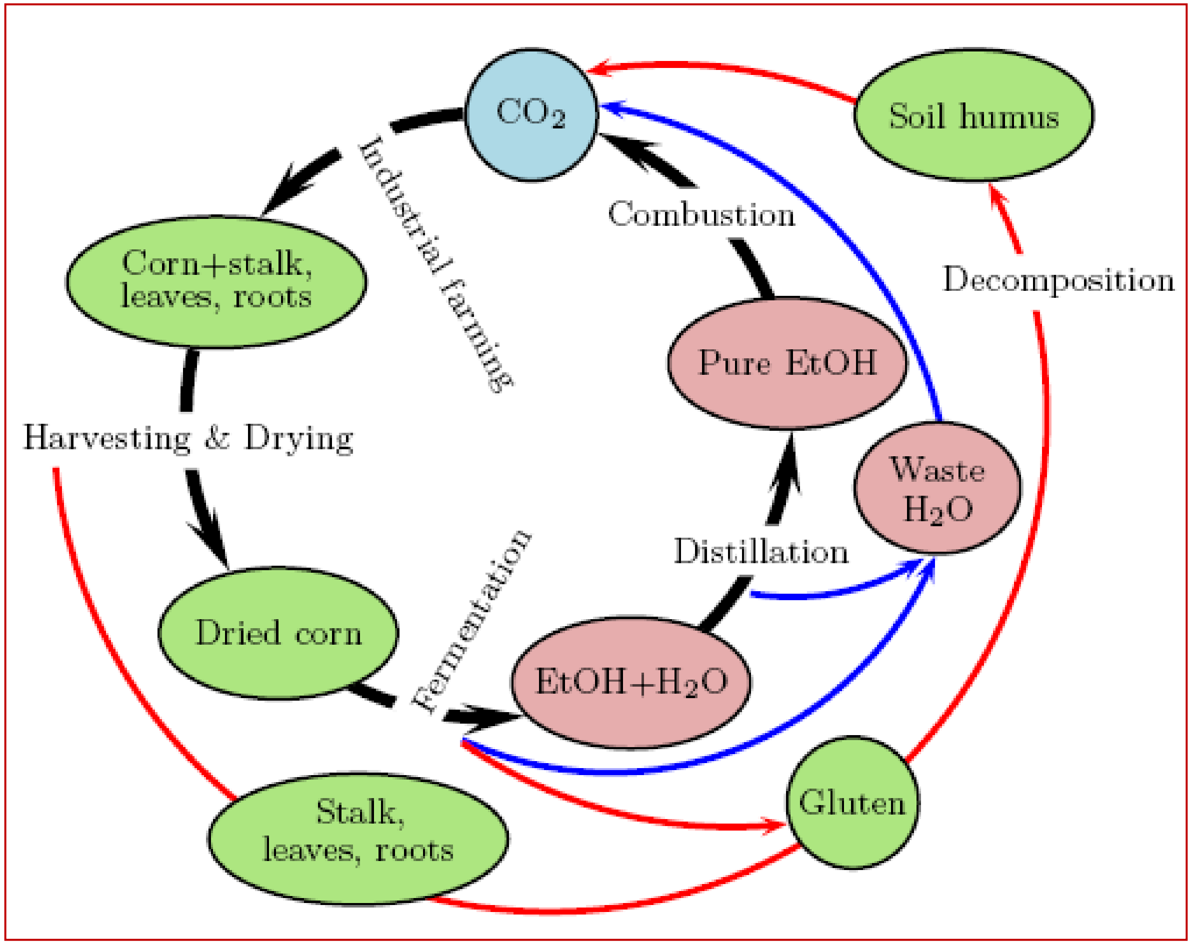
Only If $W_u > W_R$!!!



NOT SUSTAINABLE !!!

Carbon cycle in an ideal corn-to-ethanol process

- The cycle is closed (no additions to environment).
- Corn binds CO_2 from air and releases it back to the atmosphere by ethanol burning and decomposition of leftover biomass.
- Most of the biomass must be returned to the field to preserve topsoil.



Net CO_2 emissions (Patzek, 2006)

Question:

How much CO_2 does the industrial corn-ethanol cycle generate?

Calculation method:

- CO_2-equivalency is considered (other greenhouse gases)
- Specific emissions are multiplied by the respective energy input flux (MJ/ha)

Converting NO_X to equivalent CO_2

Emission from N-fertilizing the crops:

• 150 kg N Fertilizer for ha used.

•1.25% of it escapes to the air as N_2O. (150-1.875=**148.125**)

• 30% of applied N escapes from the field (surface water) out of which 2.5% converts to N_2O. (148.125-1.125=**147**)

• 10% of applied N escapes as NH_3 to the air, 1% of that becomes N_2O. (147-0.15=**146.85**)

• N_2O is 300 times more potent as a greenhouse gas (GHG) than CO_2. (150-146.85)*300=**945kg**

Emission from the ammonia plant

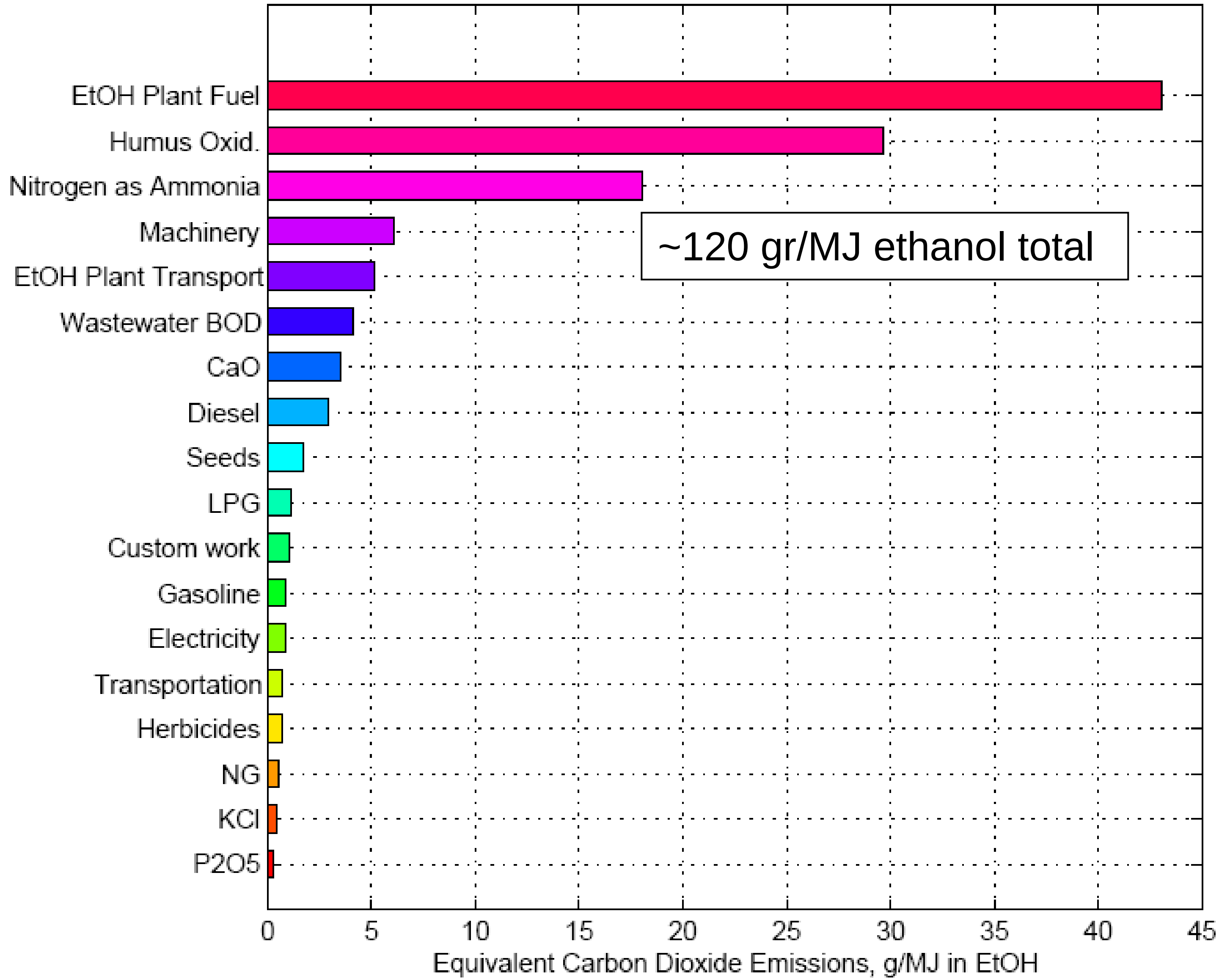
• An average ammonia plant emits 0.03 kg N_2O for 1 kg N in nitric acid used to make ammonium nitrate.
(150*0.03*300*(63/80)=**1063kg**)

NH_4NO_3 (ammonium nitrate) Mw=80 gr/mol
HNO_3(nitric acid) Mw=63 gr/mol

(All these are following guidelines of the EIA 2002)

N-Fertilizers emit an equivalent of 2008 kg CO_2 per ha corn.

Net CO_2 emissions- calculation results



65,350-68,320 MJ/ha (LHV)

CO_2 emissions – comparing to other fuels

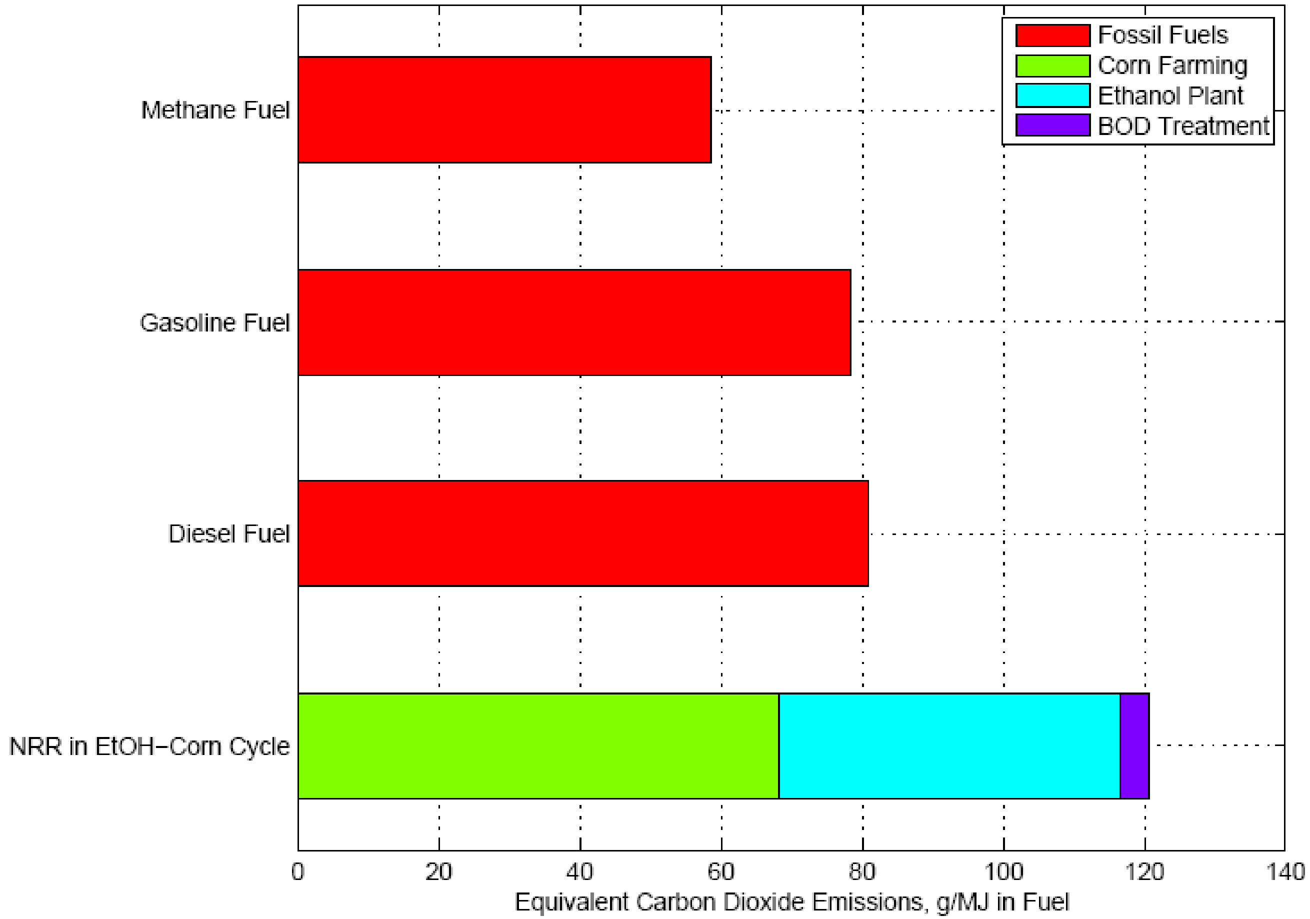


Figure 39: The total equivalent CO_2 emissions from the consumption of nonrenewable resources by the industrial corn-ethanol cycle. The CO_2 emissions from the energy-equivalent amounts of methane, gasoline and diesel fuel were increased by 17% to account for their recovery, transport, and refinement.

CO_2 emissions – conclusions

1. 1 hectare of industrial corn-to-ethanol produces ~9000 kg of equivalent CO_2.
2. Gasoline with energy content of the ethanol produced from this hectares generates 5817 kg CO_2.
3. In 2006, with 4.9 million hectares, 15.4 million tons of equivalent CO_2 **more** than the energy-equivalent gasoline.
4. To satisfy 10% of U.S. fuel consumption, an **additional** equivalent of 127 million tons CO_2 per year will be generated.

Water use in the corn-to-ethanol industrial process

Questions:

- How much water is needed for each stage of the process?
- Is there enough water?
- How are water-quality issues addressed?

Water in the corn production stage:

Quantity

Depends on local and regional considerations:

- The 2003 USDA farm and ranch survey: irrigated corn uses **3.66 $*10^6$** (L/ha).
- Israel (ministry of agriculture): **4.5-6.5 $*10^6$** (L/ha).
- Pimentel and Patzek's: **5.4 $*10^6$** (L/ha).
- **Actually irrigated** in the U.S. is 15% of the area (50% in Nebraska).
- Source of water: mining the High Plains (Ogallala) aquifer.

Water in the ethanol production stage:

Quantity

(liters water per 1 liter ethanol)

- 10-12 in corn mashing
- 20-25 in glucose fermentation
- Total is 30-37 liters.
- Using ethanol yield it equals **0.11 $*10^6$** (L/ha).

Quality

- For every liter of produced ethanol, 10-12 liters of polluted water are created.
- This water consists of proteins, sugars, enzymes, bits of dead yeast cells and some remaining alcohol.

Corn-to-ethanol requires between $3.77*10^6$ to $6.61*10^6$ (L/ha).

Is there enough groundwater?

Question:
How much water is needed in order to have 30% of the energy consumed today by gasoline come from ethanol?

Calculation:

$$\frac{(70*10^{6}\,cars)*(12{,}000\,miles/(year*car))*(116090\,BTU/gallon\_gasoline)}{(27\,miles/gallon\_gasoline)*(76000\,BTU/gallon\_ethanol)} = 4.75*10^{10}\,gallons\_of\_ethanol/year$$

- With yield of 350 gallons ethanol per acre this is 1.4 $*10^{8}$ acres (5.5 $*10^{7}$ hectares).
- In 2007 there were 9.4 $*10^{7}$ acres of corn planted.

- For this corn between 2 and 3.5 $*10^{14}$ liters water will be necessary for full irrigation
- 3.1 to 5.5 $*10^{13}$ liters for 15% irrigation.

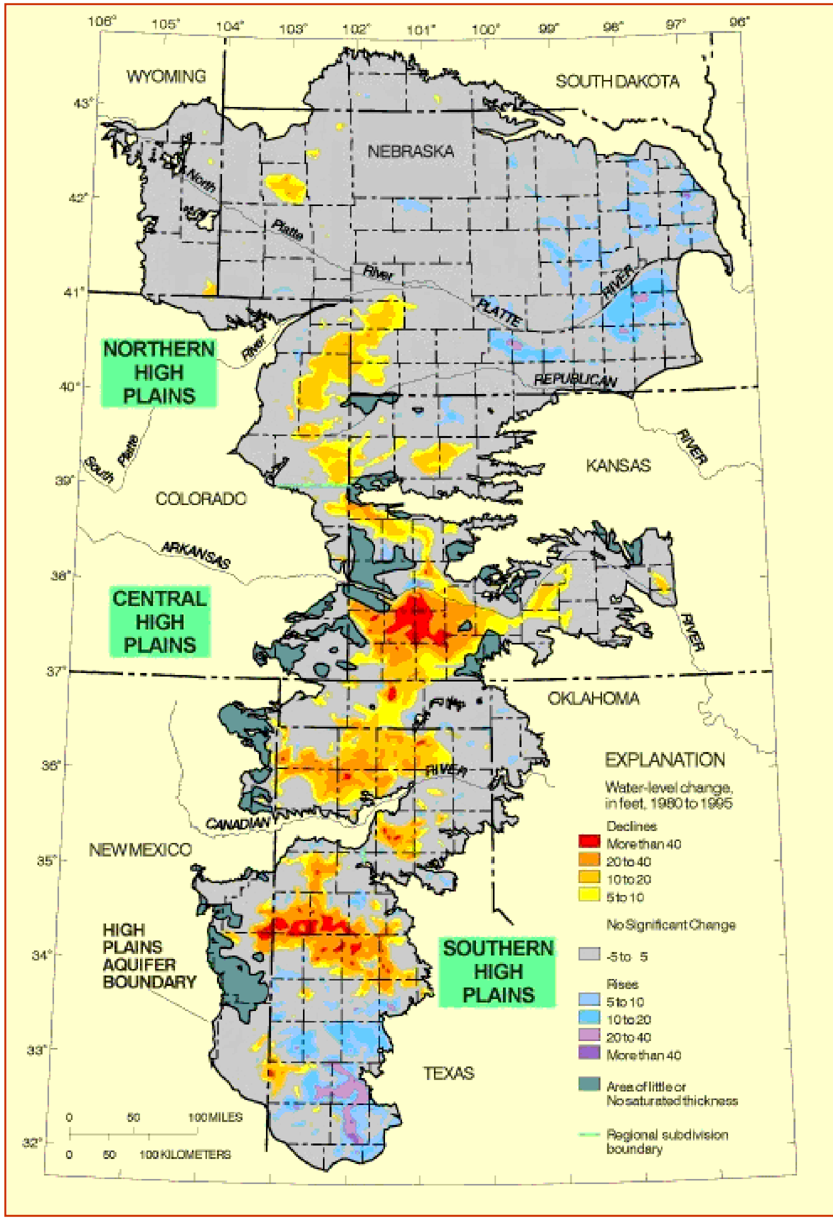
Increase pumping by 45%

Can the aquifer supply this?

The Ogallala Aquifer

The USGS estimated that **total water storage** was about 2,925 million acre feet (3,608 km³) in 2005. This is a decline of about 253 million acre feet (312 km³) (or 9%) since substantial ground-water irrigation development began, in the **1950's**.

The Ogallala Aquifer is being depleted at a rate of 12 billion m³/year. Some estimates say it will dry up in as little as 25 years. Many farmers in Texas which rely particularly on the underground source, are now turning away from irrigated agriculture as they become aware of the hazards of overpumping.



Open questions:

- Is there enough land for massive corn-to-ethanol production? (so that ethanol will be the main source for transportation fuel).
- Is there enough demand for massive co-product quantities?
- How well does corn-to-ethanol exploits the solar energy?
- How does the efficiency of corn-to-ethanol compare to other renewable energy sources?

Electricity using exercise bike

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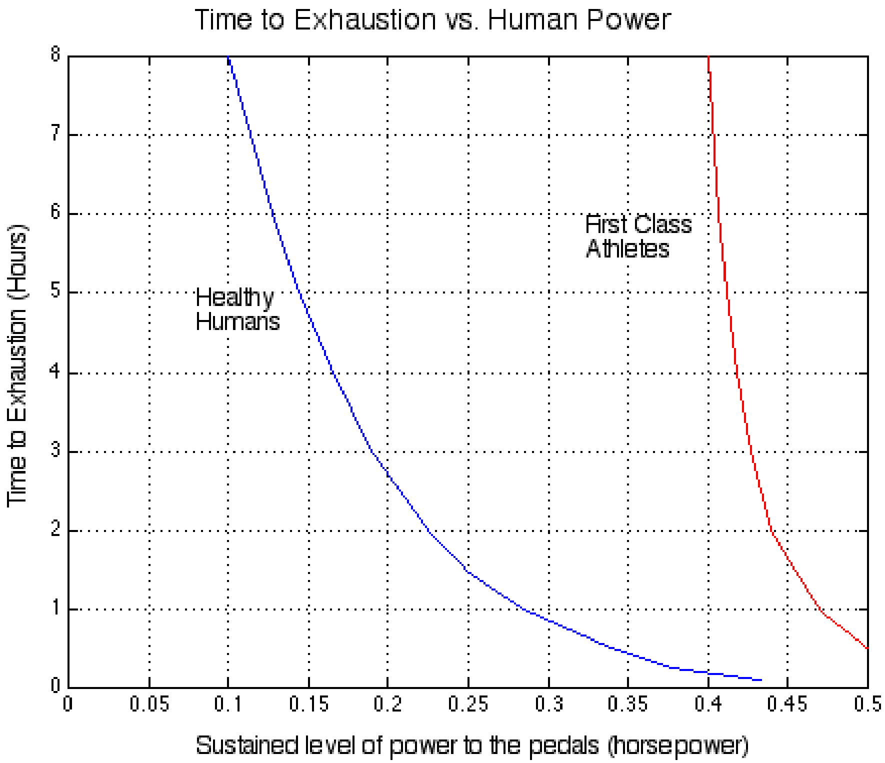

Douglas Malewicki (1983)

device	kW/hr
refrigerator	0.25
microwave	1
Tungsten light bulb	0.075
Fluorescent light bulb	0.02

0.1hp=75W

- For 1 hour of exercise an healthy human can produce 0.27 hp of mechanical work (about 200W)
- Lets take 75% of the output power (age, weight) – max power of mechanical work: 150Wh)
- Efficiency of mechanical-electricity conversion – 0.5
- Total output power: 75Wh or 0.075kWh

THE

END