

Ethanol from Corn: Just How Unsustainable Is It?

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Acknowledgements...

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- ⑥ We thank Prof. **DAVID PIMENTEL** of Cornell for the critique and several reviews of the evolving work, and kind words of encouragement
- ⑥ We thank Prof. **CLAYTON J. RADKE** of U.C. Berkeley and Mr. **MATTHEW SMALL** of the U.S. EPA for their critique and suggestions of numerous improvements

Spring 2003 CE24 Freshman Class...



Players...

Professor **DAVID PIMENTEL**, the world-famous agricultural expert from Cornell University, author of the CRC *Handbook of Energy Utilization in Agriculture* (1990), the monograph *Food, Energy, and Society* (1996), and dozens of papers on the subject of energy efficiency of agriculture

Players...

MICHAEL WANG, CHRISTOPHER SARICKS and **MAY WU**, authors of the 1997 Argonne National Laboratory Report: *Fuel-Cycle Fossil Energy Use and Greenhouse Gas Emissions of Fuel Ethanol Produced from the U.S. Midwestern Corn*

HOSEIN SHAPOURI, JAMES DUFFIELD and **MICHAEL WANG**, authors of the 2002 USDA Report: *The Energy Balance of Corn Ethanol: An Update*

Players...



YOURS TRULY, *definitely* not an agricultural expert, but a chemical engineer and physicist well-trained in thermodynamics and mathematical modeling of physicochemical processes

Corn Highlights...

- ⑥ The largest U.S. crop, ~70 million acres, yield ~130 bushels/acre
- ⑥ U.S. produces 44% of world's corn, Canada 1%
- ⑥ 99% of U.S. corn fields is fertilized
- ⑥ Requires more fertilizer than any other crop
- ⑥ Erodes soil 18 times faster than it can reform
- ⑥ Corn needs 40-65 cm water, 15% is irrigated
- ⑥ \$10 billion in corn price subsidies (Oxfam)
- ⑥ U.S. goal: Produce 5 billion gallons of ethanol from corn annually

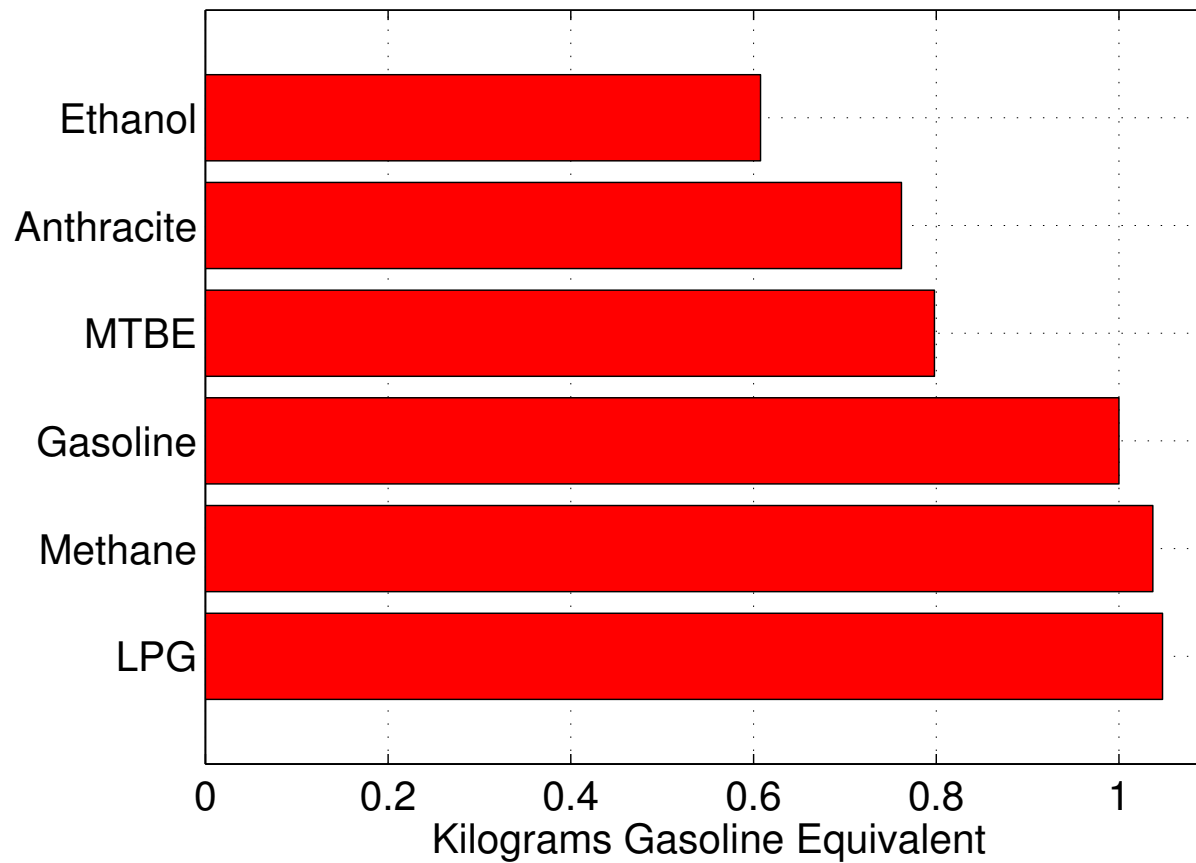
Ethanol From Corn...

- ⑥ Is a complex **engineered bio-system** with a myriad of energy inputs and outputs
- ⑥ Just collecting the major inputs and outputs is a lengthy and tedious process, full of potential inconsistencies
- ⑥ Making sense of the collected numbers is even more difficult
- ⑥ Various scientific opinions are prone to error of judgement and manipulation

⑥ ***Ethanol From Corn...***

- ⑥ The process complexity turns-off the public and politicians
- ⑥ In my opinion, today most analytic errors have been removed, and we have arrived at solid conclusions about the overall efficacy of the corn-ethanol production process
- ⑥ One should continue filtering out errors in reporting and disinformation

Fuel Energy Contents...



1 gallon of ethanol = 0.65 gallons of gasoline

Talk Outline...

- ⑥ Major energy inputs to corn production
- ⑥ Major energy inputs to ethanol production
- ⑥ Overall energy balance of ethanol production
- ⑥ Some environmental impacts of ethanol production
- ⑥ Ethanol subsidies
- ⑥ Known air quality issues with gasohol EtOH-10

Energy Inputs to Corn Production...

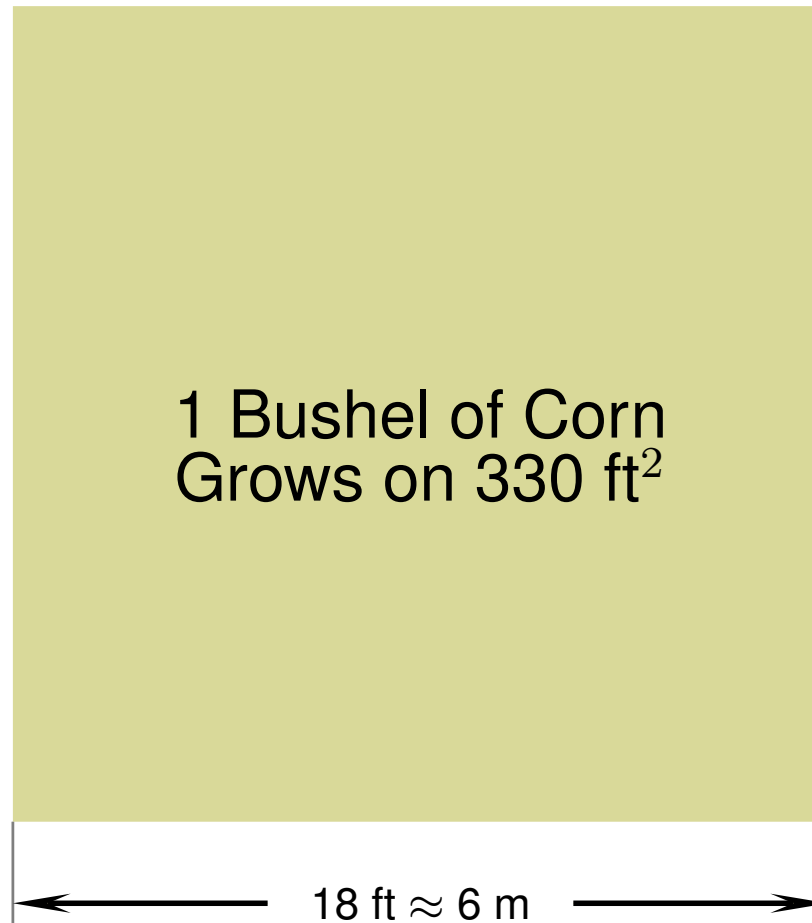
- ⑥ Nitrogen fertilizers (all fossil energy)
- ⑥ Phosphate, Potash, and Lime (some fossil energy)
- ⑥ Herbicides and Pesticides (all fossil energy)
- ⑥ Fossil Fuels (diesel, gasoline, LPG, NG)
- ⑥ Electricity (mostly fossil energy)
- ⑥ Transportation (all fossil energy)
- ⑥ Corn Seeds and Irrigation (some fossil energy)
- ⑥ Machinery, roads, silos, plants (mostly fossil energy)
- ⑥ Labor (some fossil energy)

1 Bushel of Corn Is...

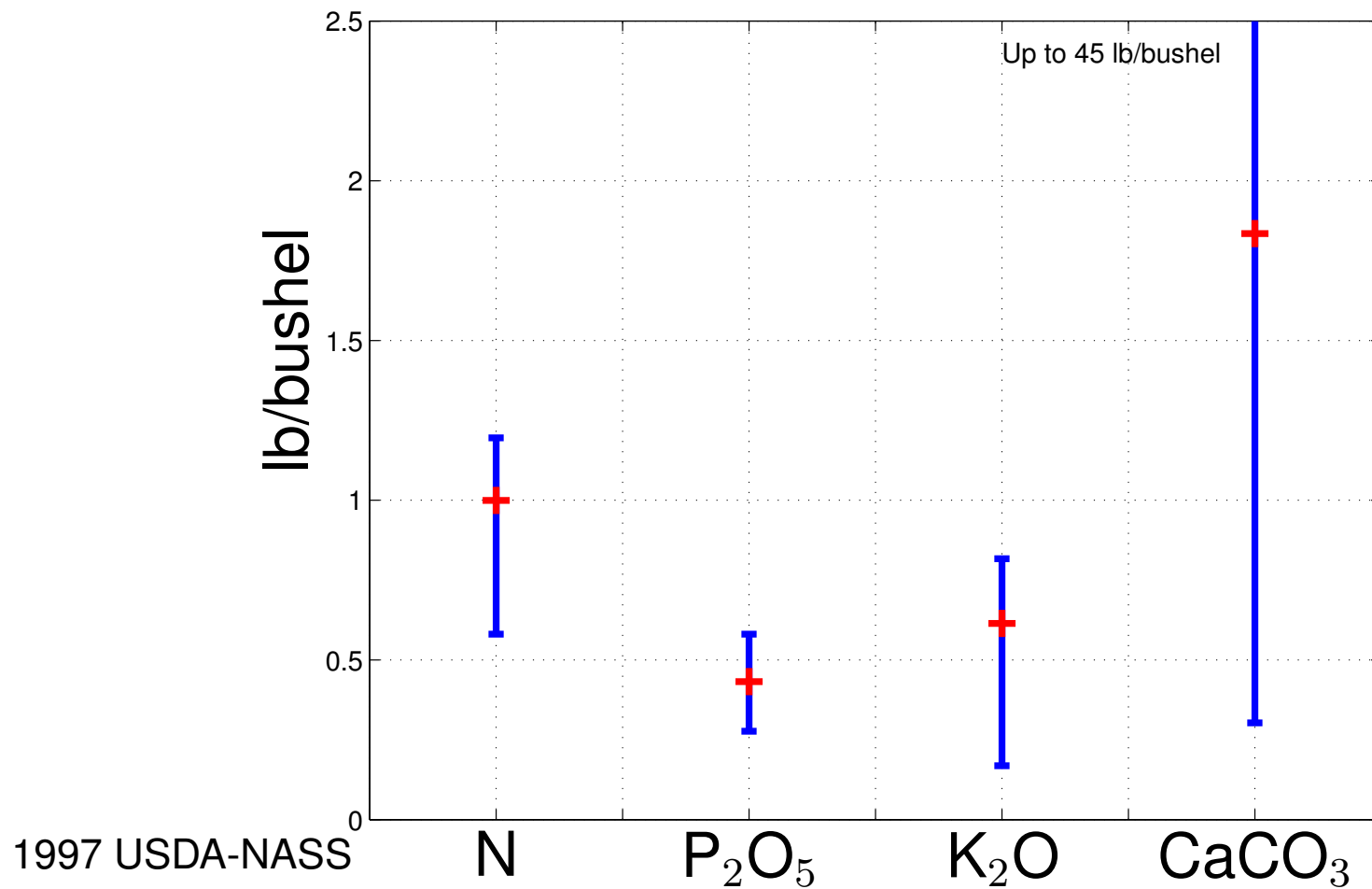


25.4 kg or 56 pounds of corn kernels with 15% moisture content ~8 gallons

1 Bushel Takes 32 m² ...



Fertilizer Uptake Per Bushel...



Nitrogen Fertilizer...

- ⑥ Is produced exclusively from **natural gas**
- ⑥ Its production requires **twice** as much energy as steel
- ⑥ Energy required to produce different nitrogen fertilizers must be expressed relative to the content of **elemental nitrogen**, N
- ⑥ All fertilizers must be transported, the most popular ones must be granulated
- ⑥ The USDA estimates of energy cost of nitrogen fertilizers (*e.g.*, Shapouri *et al.*, 2002) are too low

Forms of Nitrogen Fertilizer...

Ammonia, NH_3

- ⑥ Is obtained from N_2 and H_2 in the Haber-Bosch process
- ⑥ Hydrogen is produced by steam-reforming **methane**
- ⑥ To produce, purify, compress, and transport methane, $\sim 10\%$ of its feed: 1500 BTU/lb N

Forms of Nitrogen Fertilizer...

Ammonia, NH₃ (82% N):

- ⑥ Total energy consumption is

“30 Years Old”	55 GJ/tN = 23,700 Btu/lb N
“Modern Europe”	43 GJ/tN = 18,500 Btu/lb N
“Best Possible”	38 GJ/tN = 16,300 Btu/lb N

Source: ERNST WORRELL *et al.* *Energy Use and Energy Intensity of the U.S. Chemical Industry*, LBNL-44314, April 2000

G. KONGSHAUG *Energy Consumption and Greenhouse Gas Emissions in Fertilizer Production*, Hydro Agri Europe, Norway, 1998

Forms of Nitrogen Fertilizer...

Urea, $\text{CO}(\text{NH}_2)_2$ (45% N):

⑥ Obtained from NH_3 and CO_2 : $2\text{NH}_3 + \text{CO}_2 \rightarrow \text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O}$

⑥ Total energy per 1 lb of N is

“30 Years Old” Ammonia + 10 GJ/tN = 30,000 Btu/lbN

“Modern Europe” Ammonia + 9 GJ/tN = 22,300 Btu/lb N

“Best Possible” + 7.2 GJ/tN = 16,300 Btu/lb N

Source: G. KONGSHAUG *Energy Consumption and Greenhouse Gas Emissions in Fertilizer Production*, Hydro Agri Europe, Norway, 1998

Forms of Nitrogen Fertilizer...

Ammonium Nitrate, NH_4NO_3 (35% N):

- ⑥ Is obtained from nitric acid HNO_3 and ammonia NH_3 :
 $\text{NH}_3 + \text{HNO}_3 \rightarrow \text{NH}_4\text{NO}_3$
- ⑥ Nitric acid is obtained by burning **ammonia** over catalysts to produce NO_x
- ⑥ Total energy **per 1 lb of N** is

“30 Years Old” Ammonia + 4GJ/tN = **25,400 Btu/lb N**

Source: ERNST WORRELL *et al.* *Energy Use and Energy Intensity of the U.S. Chemical Industry*, LBNL-44314, April 2000

Other Nitrogen Fertilizer Costs...

Urea and Ammonium Nitrate **must be granulated, packaged and transported**

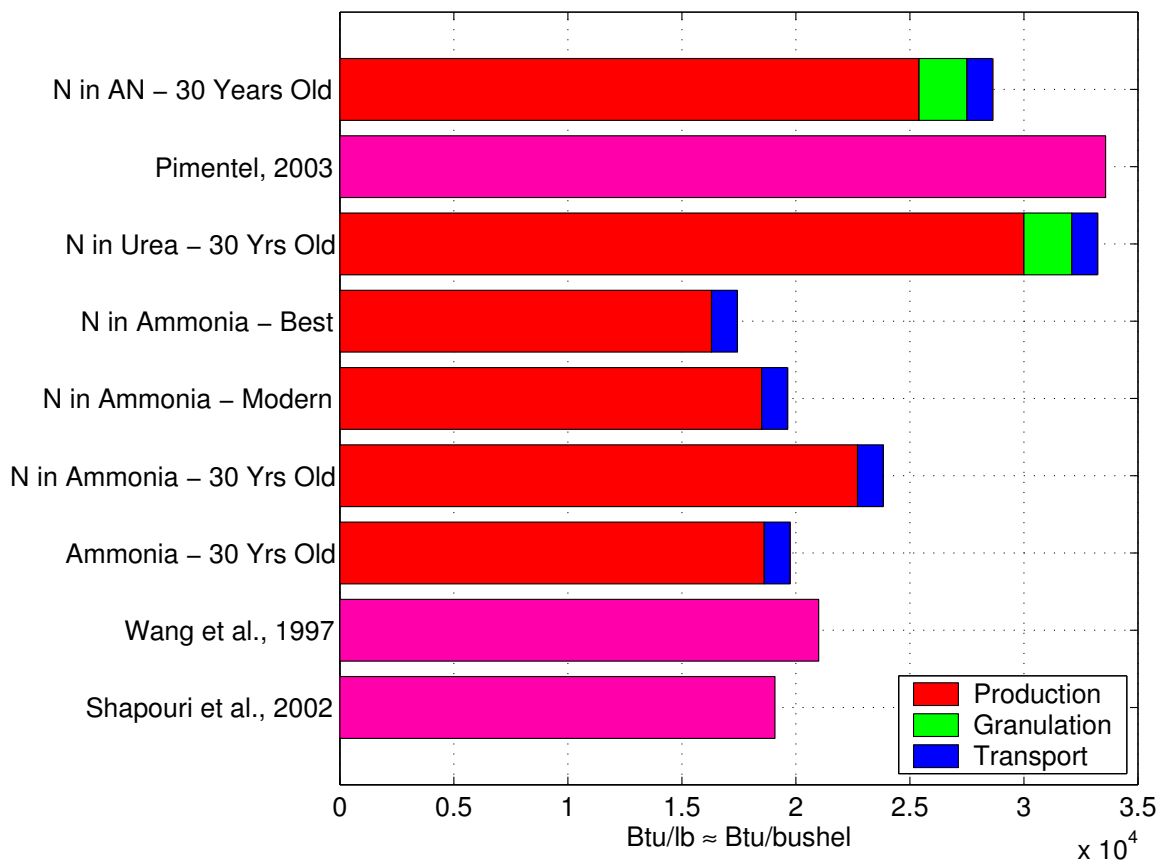
- ⑥ Energy requirement of granulation is 3.2-5 GJ/metric tonne or 2,100 Btu/lb fertilizer (~10% of their energy content)
- ⑥ The granulated fertilizer must be packaged and transported to the farmer (another ~5% of energy expenditure, or 1,100 Btu/lb fertilizer)

Sources: ERNST WORRELL *et al.* *Energy Use and Energy Intensity of the U.S. Chemical Industry*, LBNL-44314, April 2000

DENIS LAUCHARD, MARIE-ASTRID KORDEK, Kaltenbach-Thuring S.A., France

MICHAEL WANG *et al.* Argonne National Lab, 1997

Energy in Nitrogen Fertilizer...



Energy in P, K, Ca...

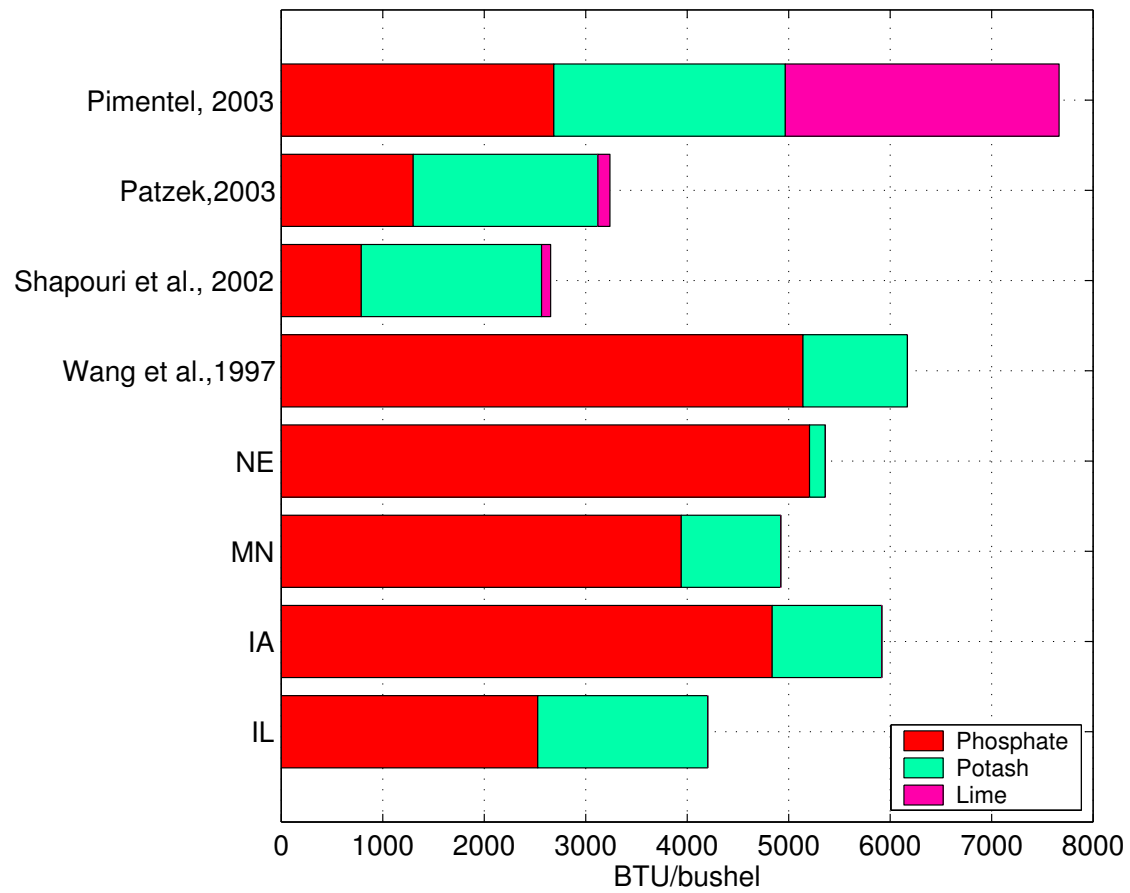
- ⑥ Total energy consumption is

Phosphate	6.7 GJ/t = 2,600 Btu/lb
Potash	6.7 GJ/t = 2,600 Btu/lb
Hydrated Lime	0.04 GJ/t = 17 Btu/lb

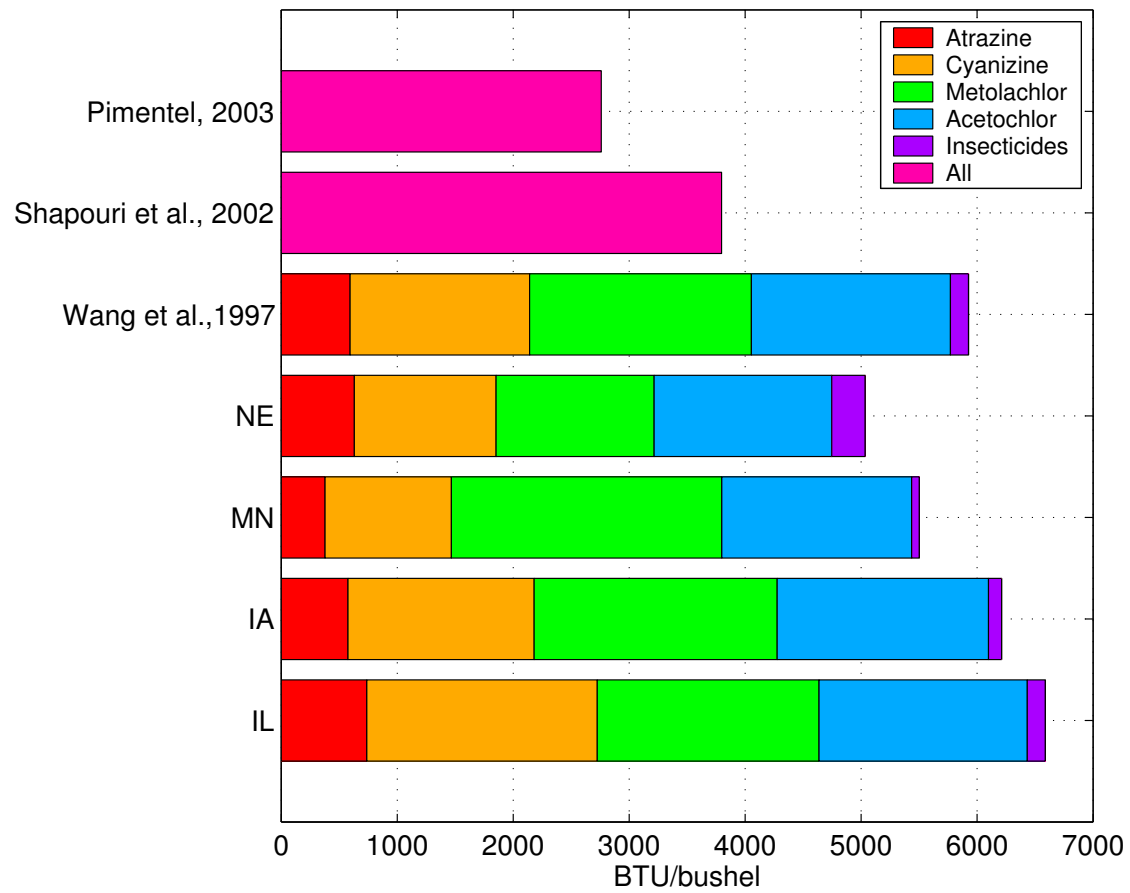
Source: Energy and Environmental Profile of the U.S. Mining Industry, Vol 9, *Limestone & Crushed Rock*, U.S. DOE, 2002

G. KONGSHAUG *Energy Consumption and Greenhouse Gas Emissions in Fertilizer Production*, Hydro Agri Europe, Norway, 1998

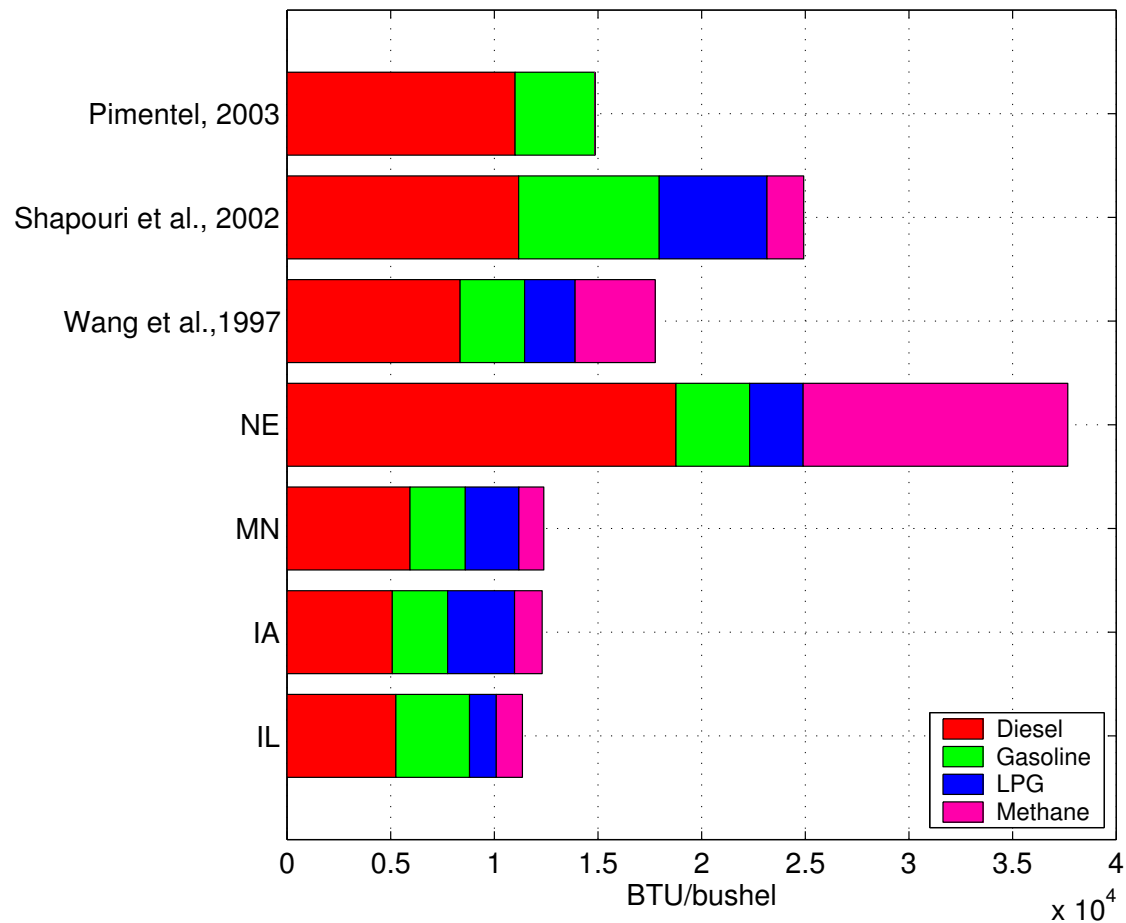
Energy in P, K, Ca...



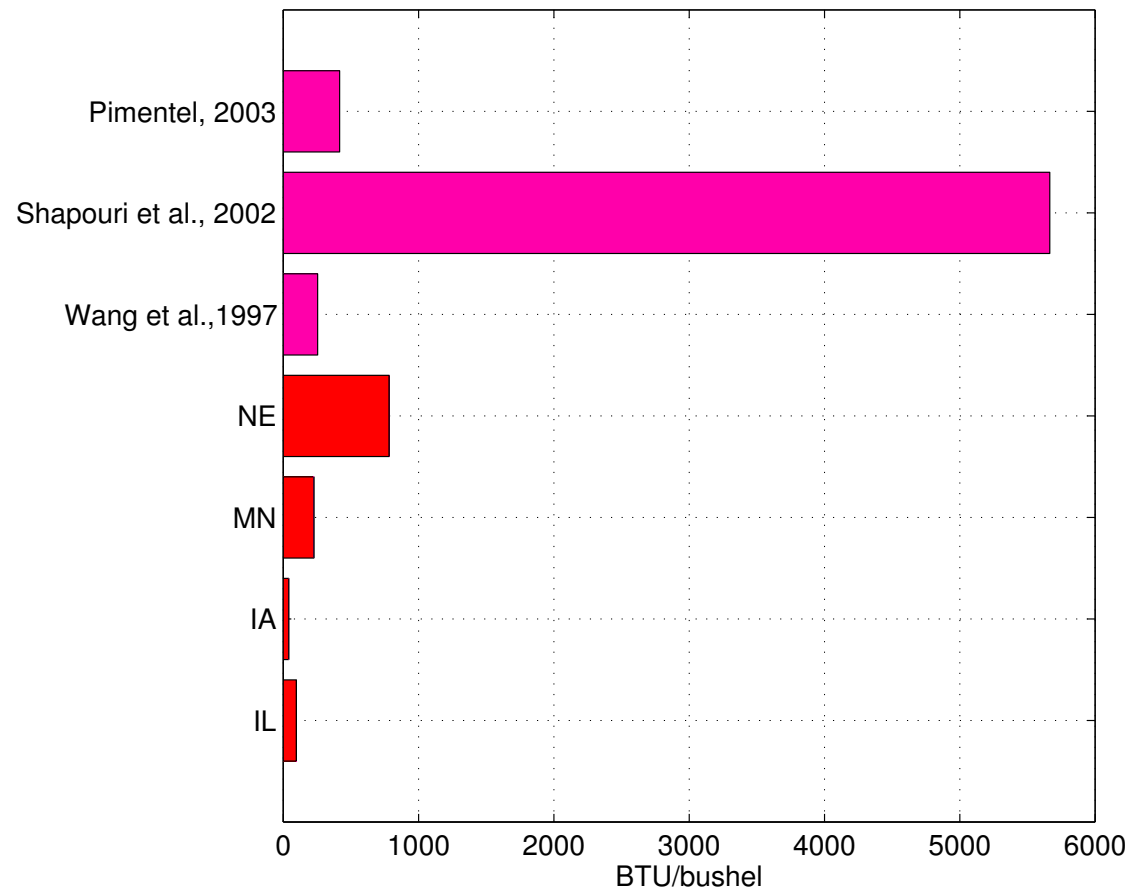
Energy in Herbicides/Insecticides...



Fossil Fuel Energy in Corn...



Energy in Electricity...



Energy in Corn Seeds...

- ⑥ Seed rate **23,000** (Corn Belt) – **30,000** (West) kernels per acre (p. 255)
- ⑥ Mean weight of 1000 corn kernels is **332** g (p. 202)
- ⑥ Caloric value of corn kernels with 13-15% moisture is **6,500** Btu/lb

$$\frac{23 \frac{1000}{\text{acre}} \times 332 \frac{\text{g}}{1000}}{454 \frac{\text{g}}{\text{lb}} \times 132 \frac{\text{bushel}}{\text{acre}}} \times 6,500 \frac{\text{Btu}}{\text{lb}} = 828 \text{ Btu/bushel}$$

Source: *Corn Chemistry and Technology*, AACCC, 2003

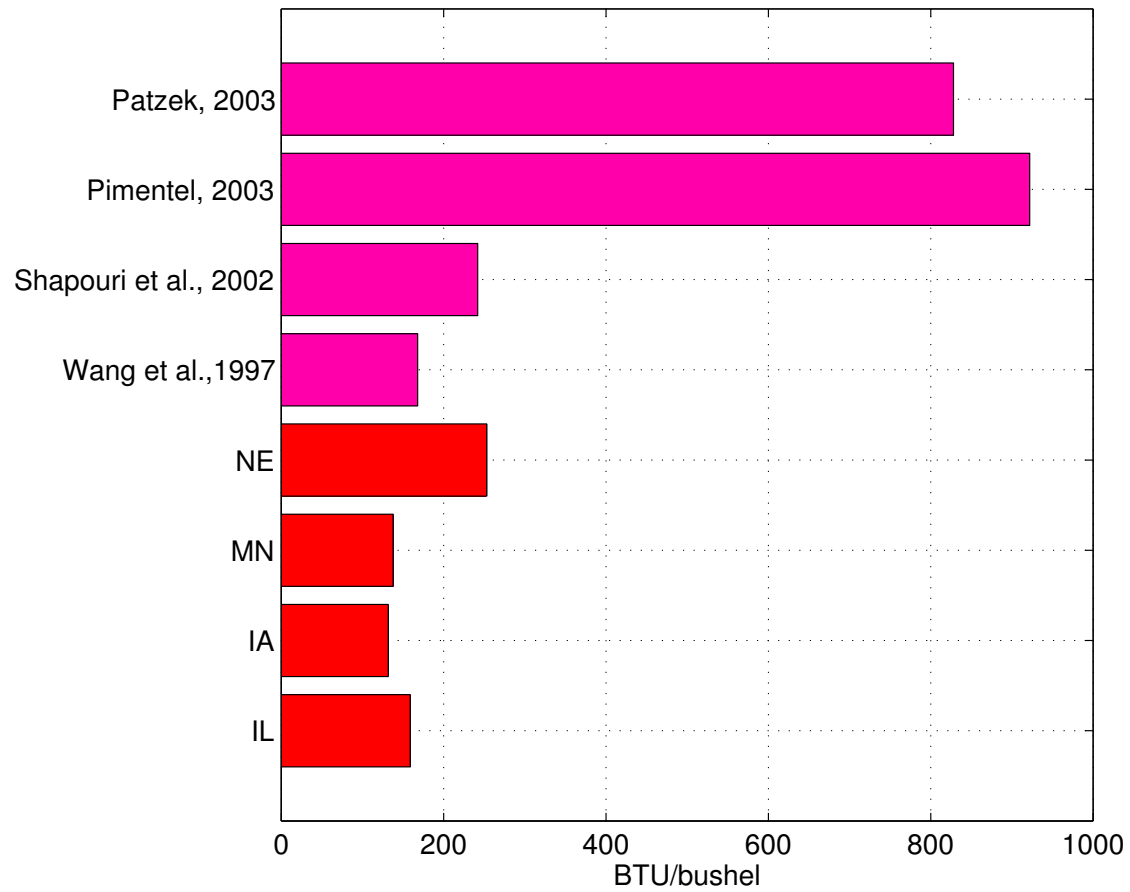
Energy in Corn Seeds...



Bottom line:

- ⑥ I have used the lowest seed grain density of 23,000 kernels/acre
- ⑥ PIMENTEL (2003) and SHAPOURI *et al.* (2002) used 25,500 kernels/acre
- ⑥ Consequently, SHAPOURI *et al.*'s estimate should agree exactly with PIMENTEL's; instead, it is 4 times lower

Energy in Corn Seeds...



Energy in Irrigation...

- ⑥ Only 15% of 132 bushels/acre crop is irrigated
- ⑥ On average 8.1 cm of water is used per acre (Pimentel, 2003)
- ⑥ Water is pumped on average from depth of 100 m
- ⑥ Pump efficiency, *etc.* is 0.75

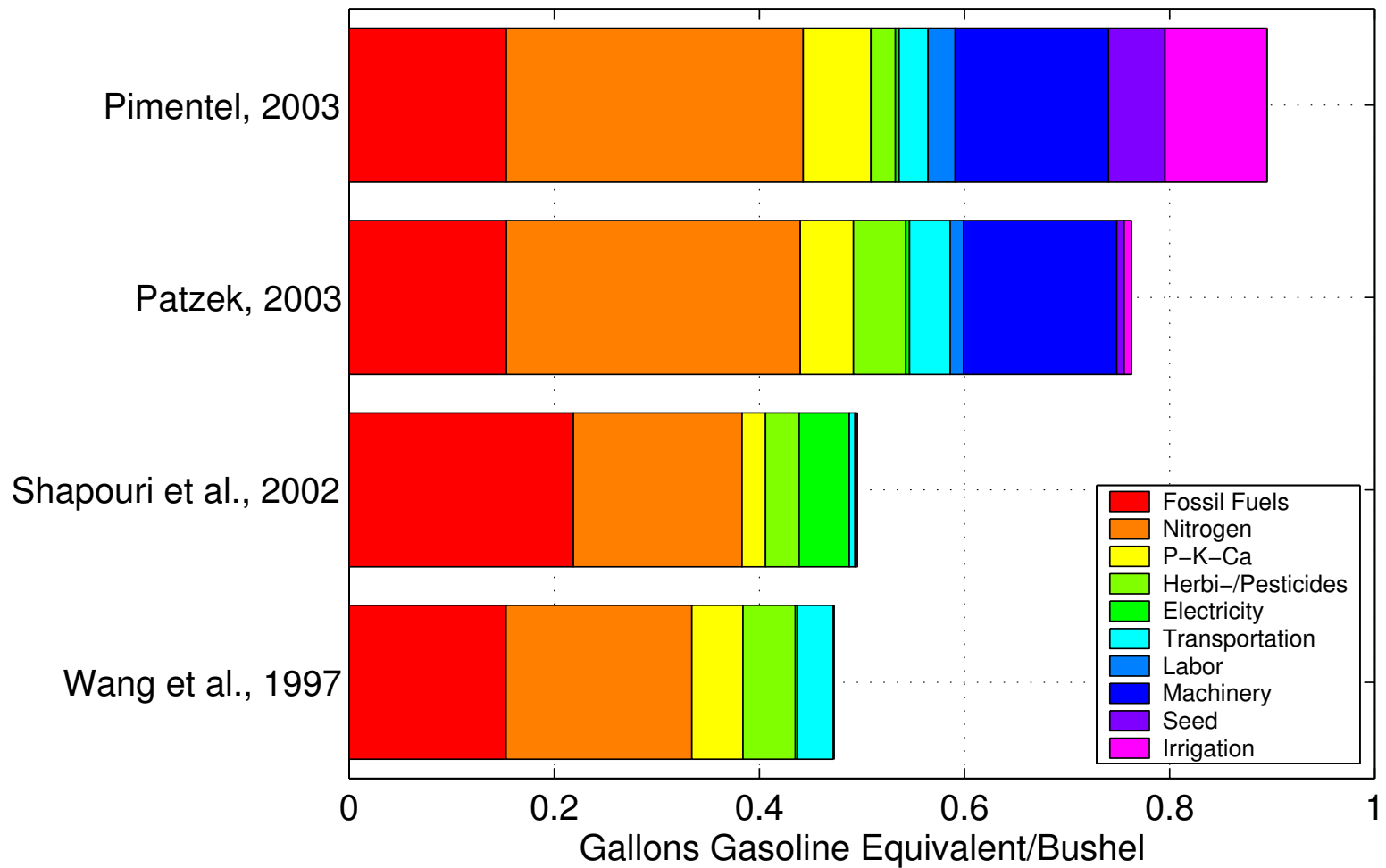
$$\begin{aligned} & 0.081 \text{ m} \times 10,000 \frac{\text{m}^2}{\text{ha}} \times 0.4047 \frac{\text{ha}}{\text{acre}} \times 1000 \frac{\text{kg}}{\text{m}^3} \times \\ & \times 100 \text{ m} \times 9.81 \frac{\text{m}}{\text{s}^2} / 0.75 = 4.2877 \times 10^7 \text{ J/acre} \\ & = 308 \text{ Btu/bushel} \end{aligned}$$

Energy in Labor...

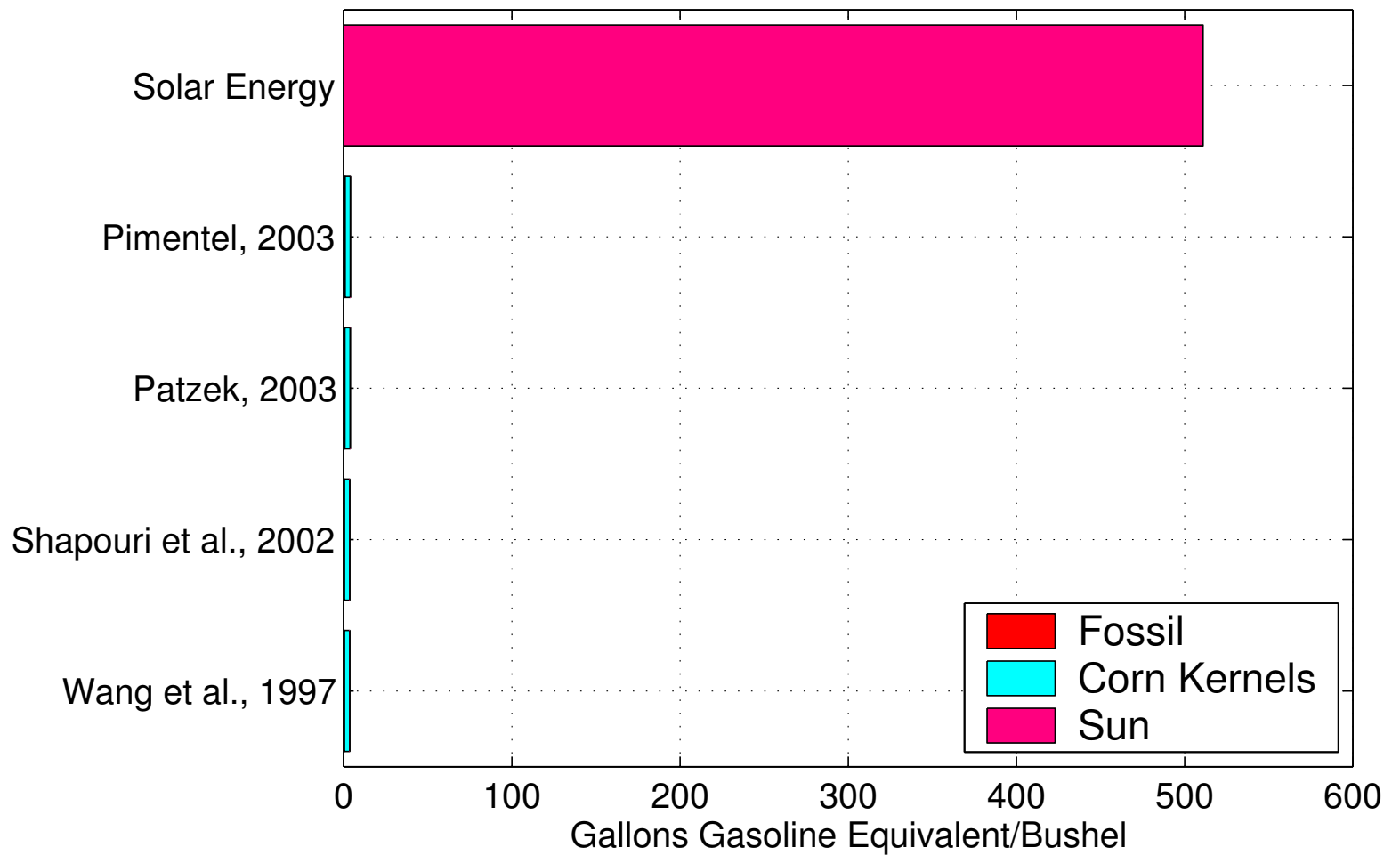
- ⑥ Labor time is 6.2 hrs/day/ha in a growth season of 120 days (USDA-NASS, 1999)
- ⑥ A physical worker is on 4,000 kcal/day diet
- ⑥ Crop yield is 132 bushels/acre

$$\begin{aligned} & 4 \times 10^6 \text{ cal/day} \times 4.186 \frac{\text{J}}{\text{cal}} \times \frac{6.2 \text{ hr/ha}}{24 \text{ hr}} \times \\ & \times 0.4047 \frac{\text{ha}}{\text{acre}} \times \frac{1 \text{ acre}}{132 \text{ bushel}} \times 123 \text{ day} \\ & = 1.6 \text{ MJ/bushel} = 1500 \text{ Btu/bushel} \end{aligned}$$

Fossil Energy Inputs into Corn...



Solar Energy Input into Corn...



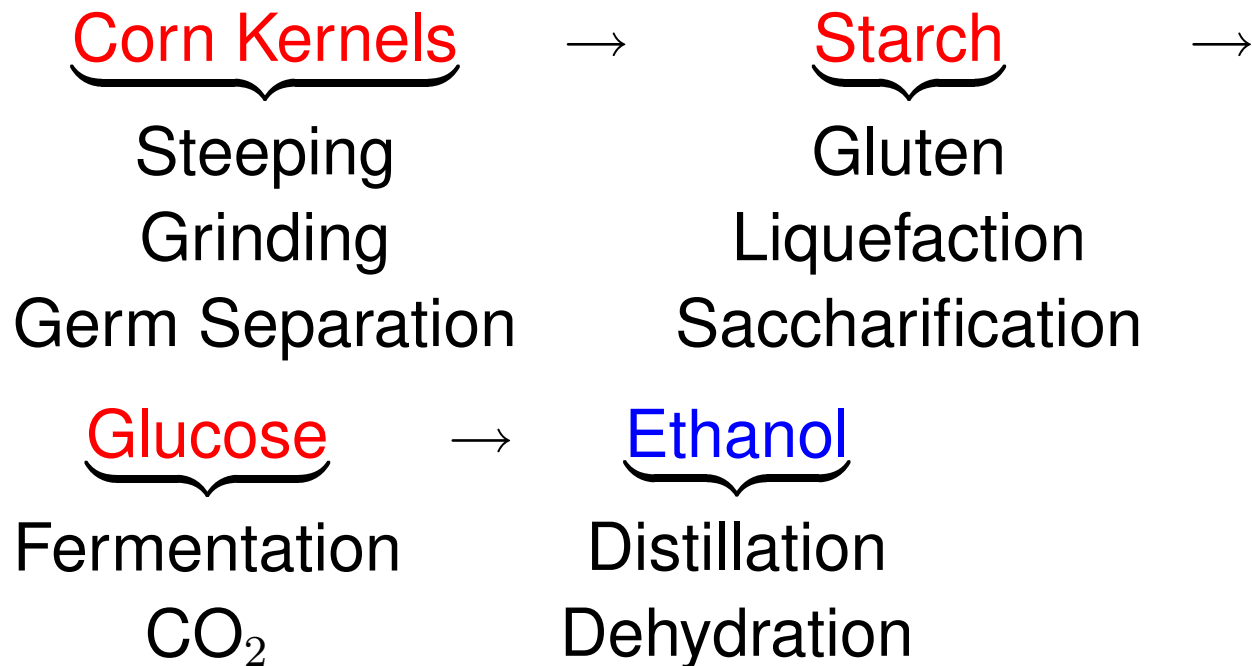
Summary of Energy Inputs...

- ⑥ WANG *et al.* (1997) and SHAPOURI *et al.* (2002) omit certain energy inputs (machinery, irrigation, labor) and underestimate others in different combinations (nitrogen fertilizer, lime, seeds, herbicides/pesticides)
- ⑥ PIMENTEL (2003) seems to overestimate the energy content of corn seeds, and the energy cost of irrigation

Summary of Energy Inputs...

- ⑥ The estimates of fossil energy inputs range from **0.47** gallons of gasoline equivalent (GGE)/bushel (WANG) to **0.89** GGE/bushel (PIMENTEL)
- ⑥ My estimate is **0.76** GGE/bushel
- ⑥ Solar energy is *not* the limiting factor in corn production: **soil**, **water**, and **dissolved nutrients** are

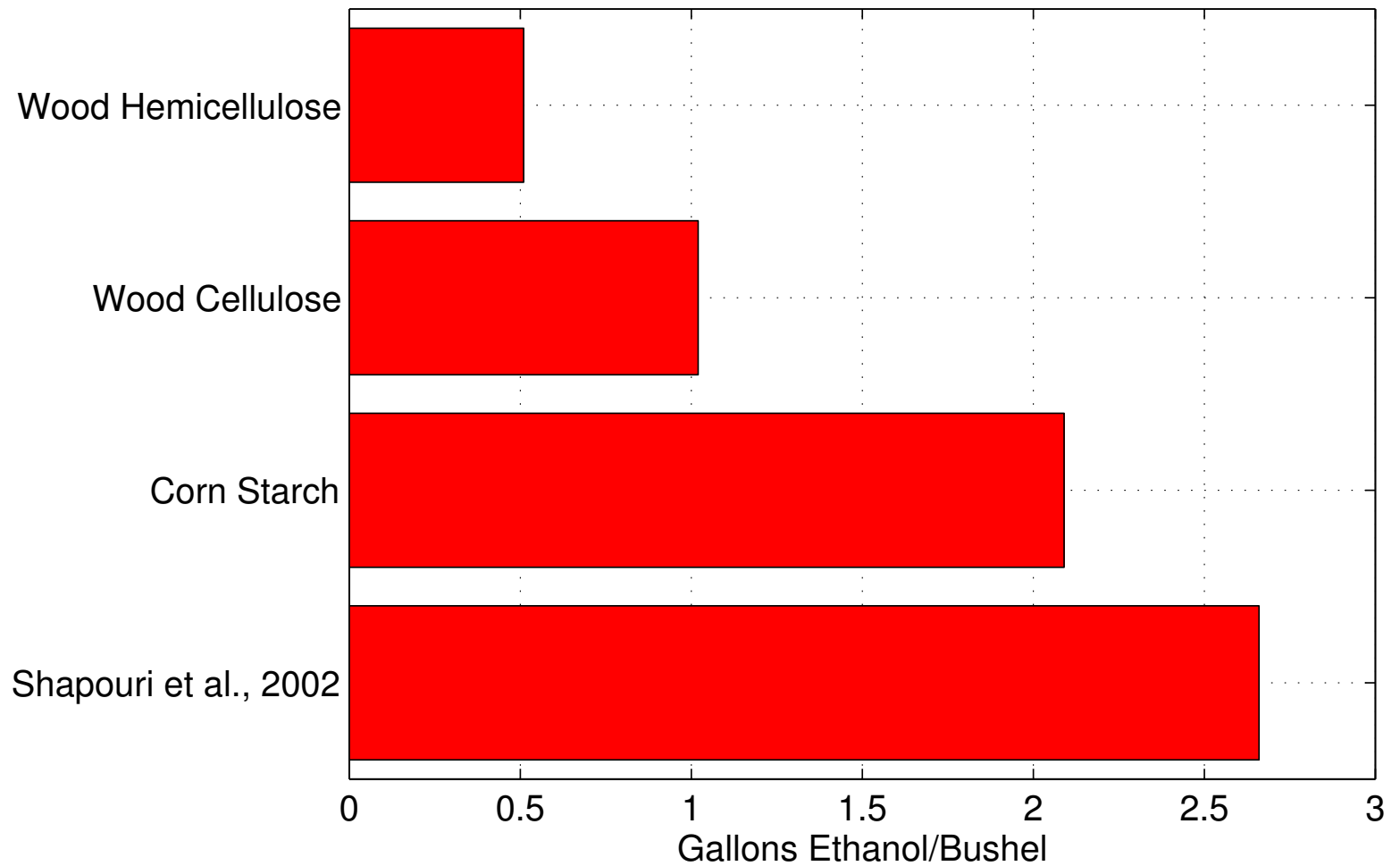
Corn to Ethanol...



Accounting Problems...

- ⑥ 66-68% of wet-milled corn kernels is starch
- ⑥ Starch is hydrolized and converted to glucose with 90-100% efficiency
- ⑥ Glucose is fermented to industrial beer with 51% efficiency (chemistry) and yield efficiency of 77-88%
- ⑥ Beer is distilled and dewatered with 100% efficiency
- ⑥ To get to 2.66 gallons of ethanol per bushel of corn, the **maximum efficiency** of each step must be achieved

Conversion of Corn to Ethanol...

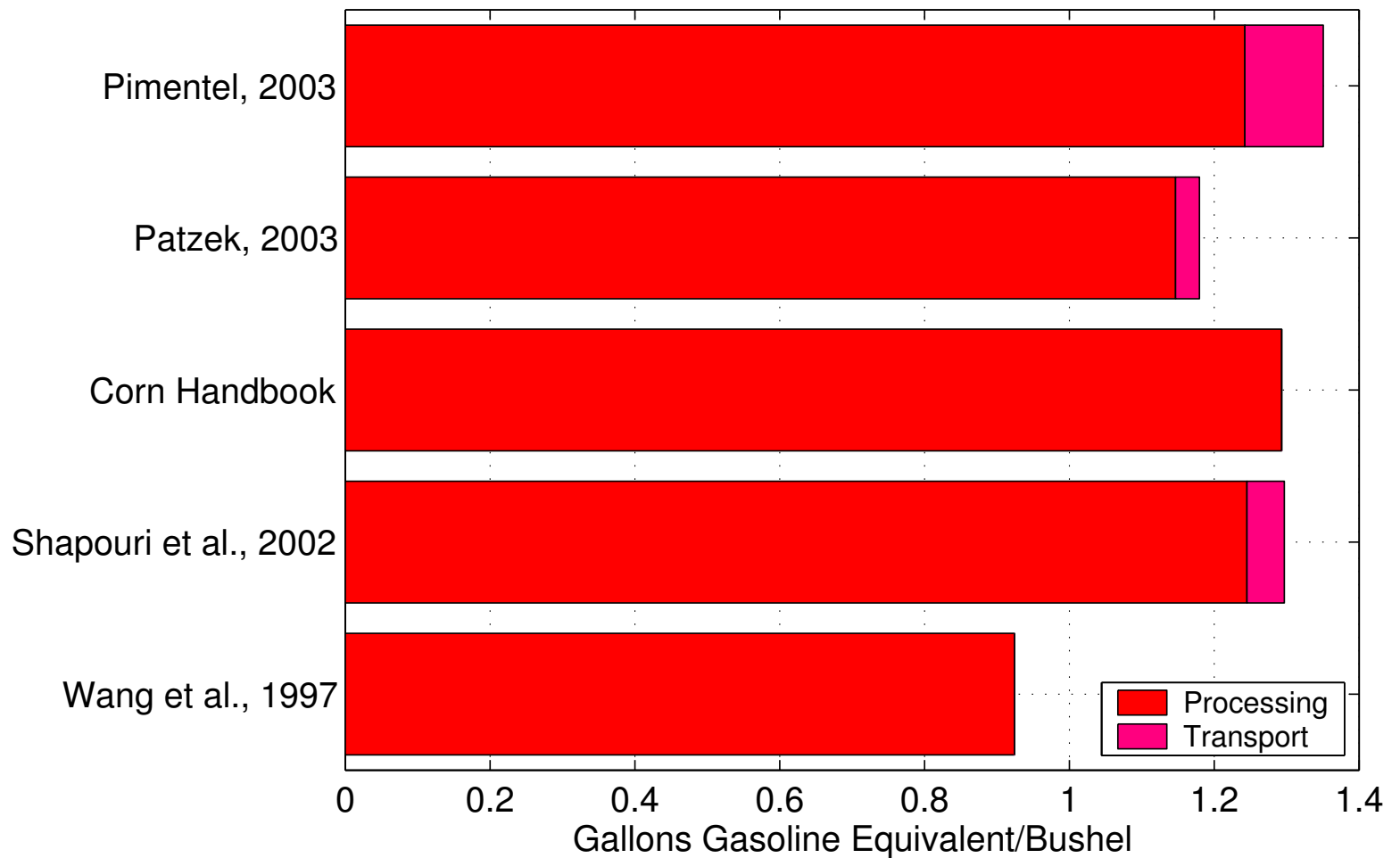


For Sale: Tucumcari Plant...



- ⑥ Produces **8,220** gallons of ethanol per day, running at 110% - 115%
- ⑥ Uses **200,000** lbs of grain per day
- ⑥ Plant efficiency is **2.3** gallons of ethanol per bushel of corn

Energy Inputs to Ethanol...



Raw Corn Products...



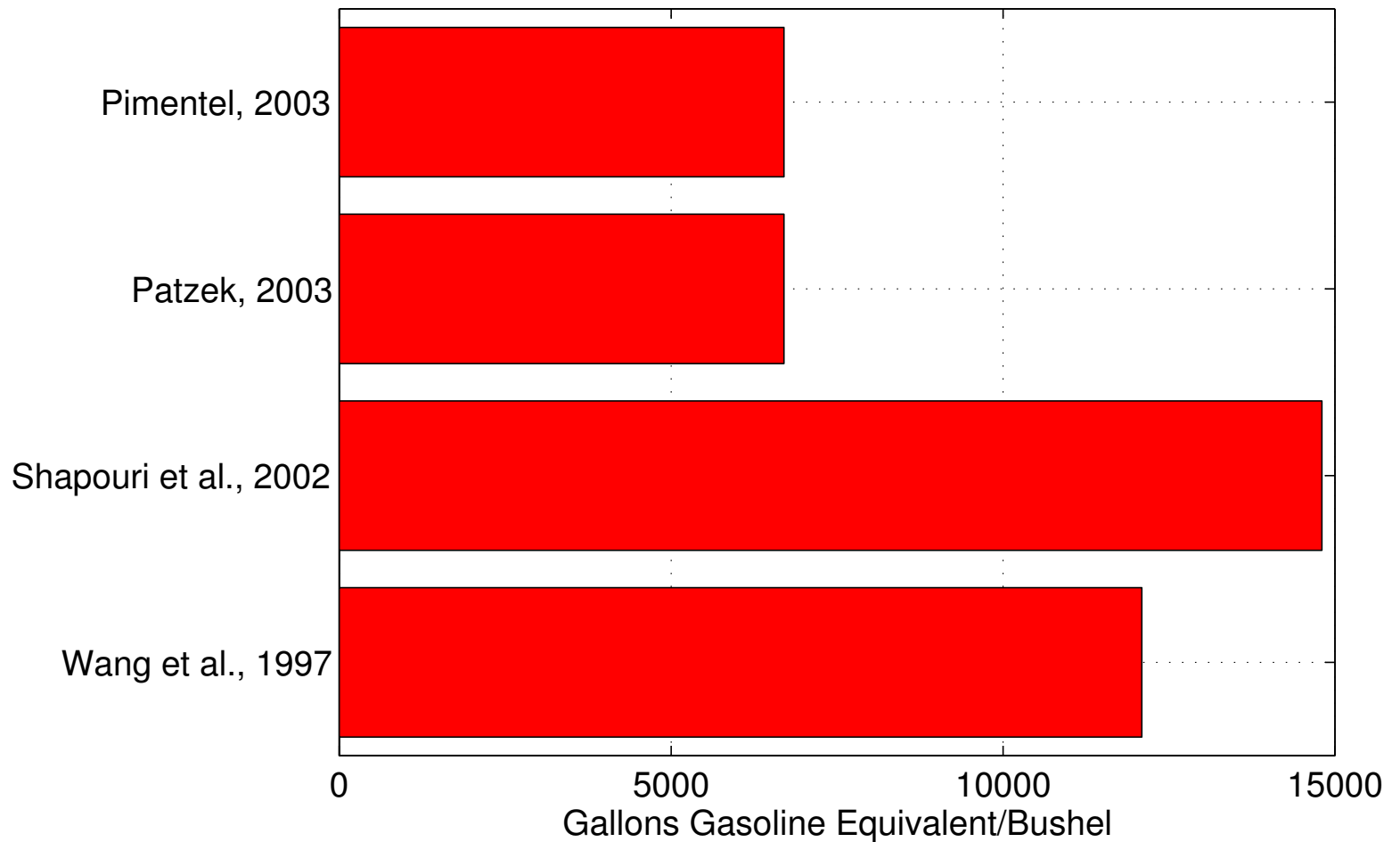
On dry mass basis:

- ⑥ Starch, 66%
- ⑥ Oil, 3.9%
- ⑥ Gluten feed (21% protein), 24%
- ⑥ Gluten meal (60% protein), 5.7%
- ⑥ Losses, 0.4%

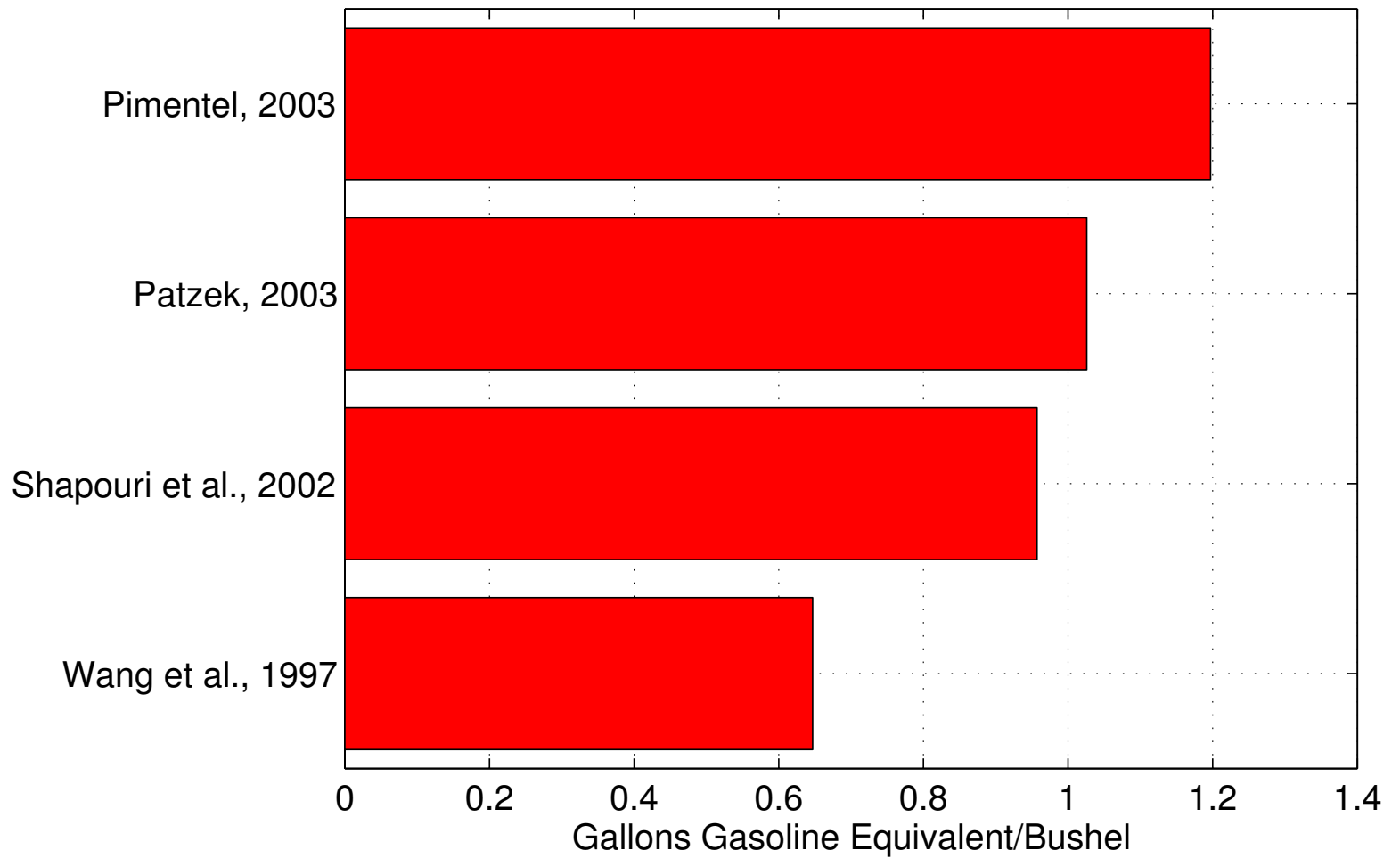
Energy Credits...

- ⑥ WANG *et al.*, 30% of energy inputs (10-year average market value)
- ⑥ SHAPOURI *et al.*, 14,804 Btu/gal of ethanol (replacement of soybean meal with corn gluten feed and meal)
- ⑥ PATZEK and PIMENTEL, 6,700 Btu/gal of ethanol (replacement of distiller's dried grain (30% protein, 8% fat) in dry milling; soybean replacement is not clear)

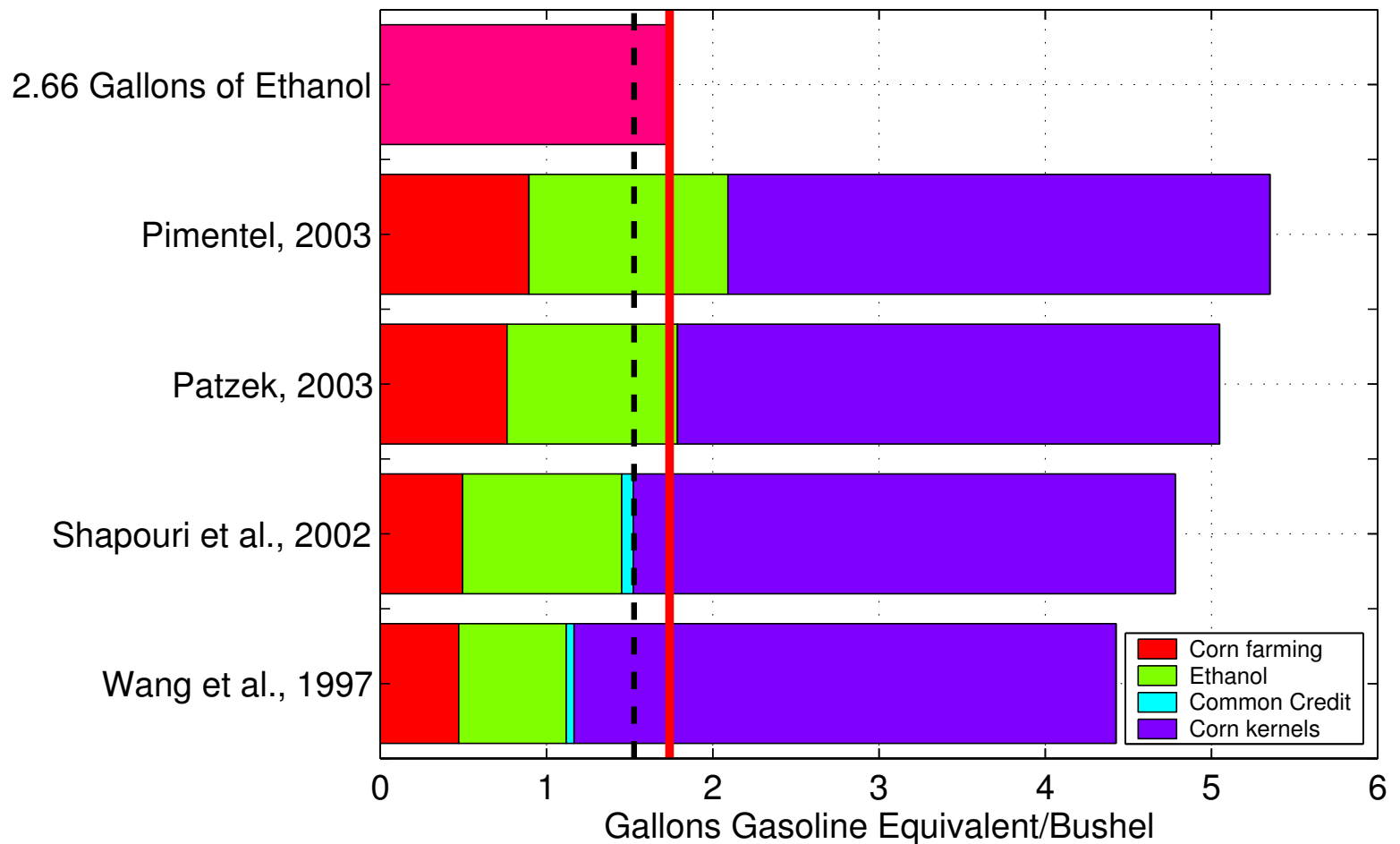
Energy Credits to Ethanol...



Net Energy Inputs to Ethanol...



Overall Energy Balance...



Bottom Line...

Ethanol production from corn is a **fossil-energy-losing** proposition:

- ⑥ Given a reasonable ethanol plant output, **2.3** gallons of ethanol/bushel (**86%** of theoretical efficiency), 3 out of 4 estimates predict fossil energy losses in ethanol production, **excluding** the energy in corn kernels
- ⑥ The estimates by SHAPOURI *et al.* (2002) are in some ways more accurate than those by WANG *et al.* (1997), but still too low
- ⑥ My estimates agree most with those by PIMENTEL (2003)

How Much Water?

Ethanol production is water-intensive. Per **1 gallon of ethanol**, one needs:

- ⑥ 38-45 liters (10-12 gal) for corn fractionation (p. 450)
- ⑥ 75-95 liters (20-25 gal) in fermentation (p. 697)
- ⑥ The total is **113-140** liters (**30-37** gal) of water per 1 gallon of ethanol!

Source: *Corn Chemistry and Technology Handbook*, 2002

And How Much Waste?

According to the *Corn Chemistry and Technology Handbook*:

- ⑥ A wet milling plant can generate as much waste as a **medium-size city** (p. 470)
- ⑥ 5-day BOD of waste water is **1,000-2,000** mg/L
- ⑥ Waste content is **0.35** lb BOD₅/bushel

Court Settlement...

12 Minnesota ethanol plants agreed to **each** spend \$2 million per plant, pay penalties \$29,000-\$39,000, and limit

- ⑥ Volatile organic compounds by **2,400 - 4,000 tons** per year
- ⑥ Carbon monoxide emissions by **2,000 tons** per year
- ⑥ Nitrogen oxides emissions by **180 tons** per year
- ⑥ Particulate matter by **450 tons**
- ⑥ Other hazardous air pollutants by **250 tons**

CAT LAZAROFF - ENS, 3 Oct 2002

So What Have We Achieved?

We have

- ⑥ **Burned** more fossil fuels than the energy content of the ethanol from corn
- ⑥ **Degraded** and **eroded** soil on millions of acres
- ⑥ **Polluted** surface and groundwater with nitrates, herbicides, pesticides, and ethanol waste
- ⑥ **Polluted** air with CO, NO_x, SO₂, VOC, *etc.*
- ⑥ Continued to waste **\$ billions** of taxpayers' money
- ⑥ Devised a **terrible** solution of air quality problems

Federal Ethanol Subsidies...

- ⑥ U.S. pays its corn farmers \$10 billion a year in subsidies (8.6% cropland for ethanol)
- ⑥ Federal excise taxes per gallon of fuel: \$0.184 for gasoline and \$0.132 for EtOH-10 (10 vol% ethanol)
- ⑥ Relative to gasoline, federal tax breaks per 1 gallon of ethanol are

$$10 \times (\$0.184 - \$0.132) = \$0.52$$

Source: Corn subsidies, OXFAM; Excise Taxes, REUTERS, Washington, Nov. 15, 2003

State Ethanol Subsidies...

- ⑥ State excise taxes per gallon of fuel:
 - △ Gasoline \$0.075 in Georgia, up to \$0.36 in Connecticut;
 - △ EtOH-10 0\$ in Arizona, up to \$0.2535 in West Virginia

- ⑥ MN offers a \$0.20 tax subsidy on EtOH-10. The state's 13 ethanol plants receive up to \$3 million a year

2002 Ethanol By the Numbers...

2.3-2.66 gallons	of ethanol from 1 bushel of corn
2.13 billion gallons/yr	of ethanol produced in the U.S.
1.38 billion GGE/yr	as ethanol produced in the U.S.
1.44 billion GGE/yr	burned to produce this ethanol
1.1 %	of U.S. automobile fuel from ethanol
6 million acres	of U.S. land growing corn for ethanol
57 million acres	for 10% U.S. automobile fuel energy
\$1.1 billion/yr	in federal subsidies for ethanol
\$0.87 billion	in corn-for-ethanol price subsidies

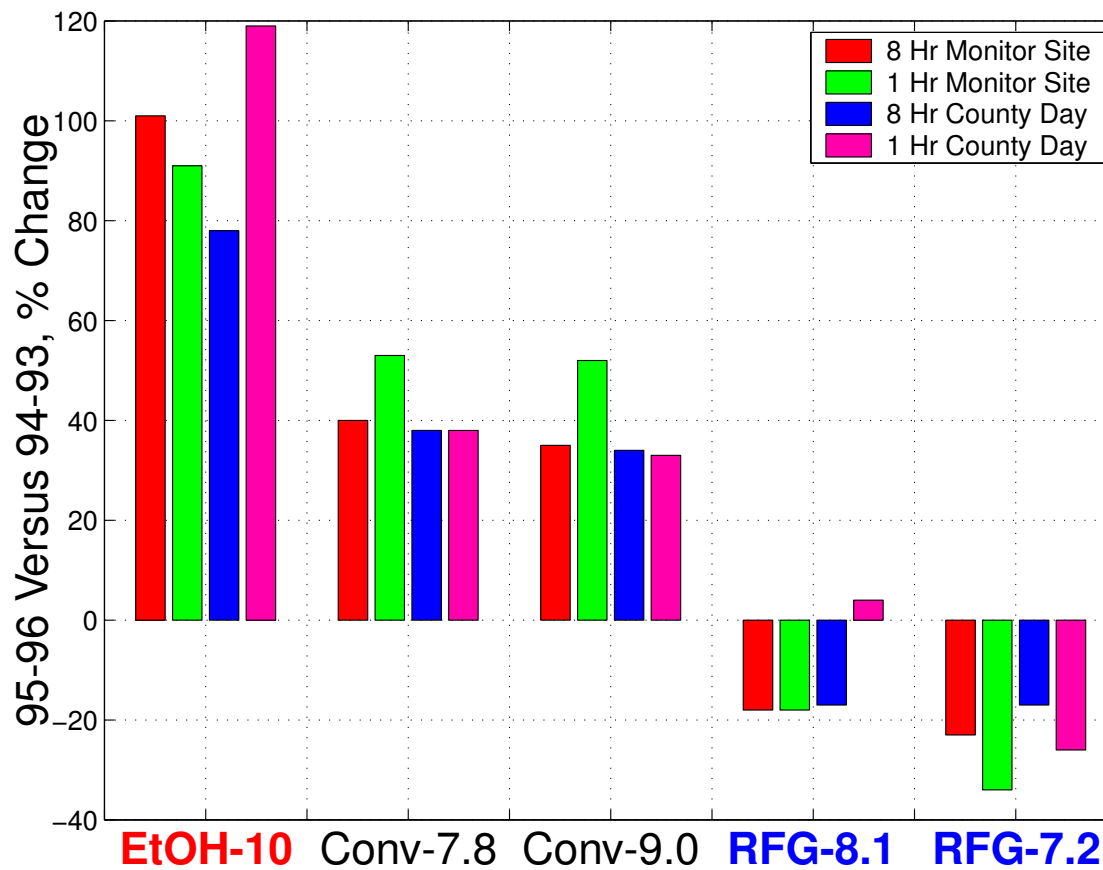
GGE = Gallons of Gasoline Equivalent

Unsafe Experiment?...

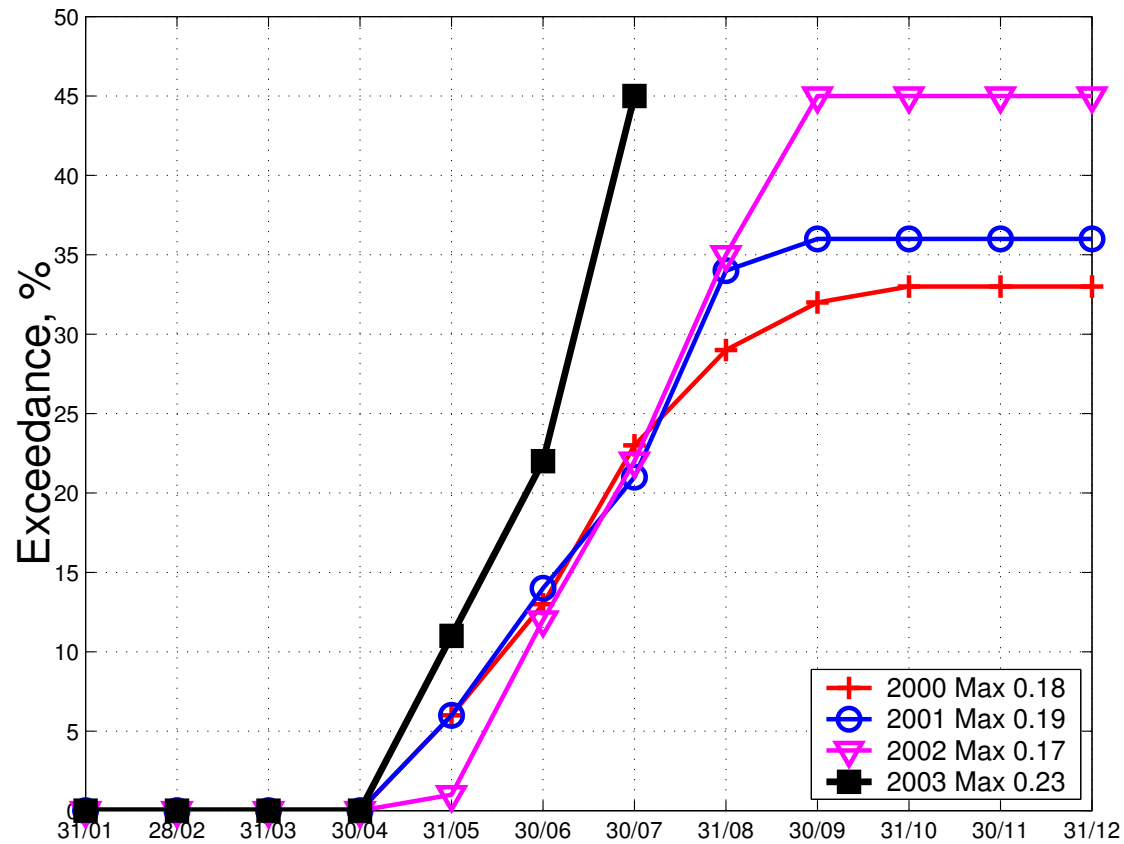
Unbeknownst to us, a gigantic experiment with our lungs and pockets has started:

- ⑥ Over **70%** of gasoline produced in Southern California has switched from MTBE to ethanol
- ⑥ The Federal ozone level exceedances in Southern California have jumped up
- ⑥ **10** vol% ethanol blends have a **70-point** poorer driveability index than MTBE or hydrocarbon blends
- ⑥ EtOH-10 gasoline blends have **6** times higher permeation emissions

Higher Ozone Levels...

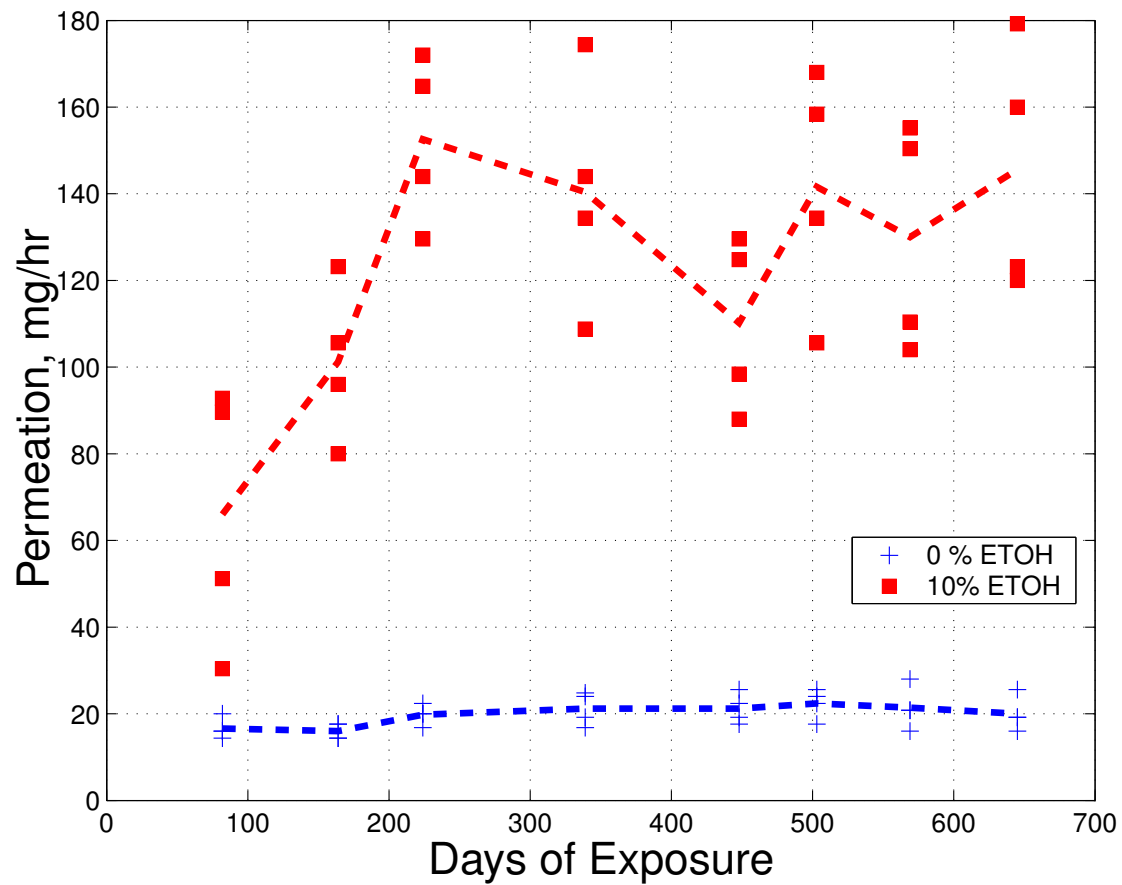


1-Hour Ozone Exceedance...



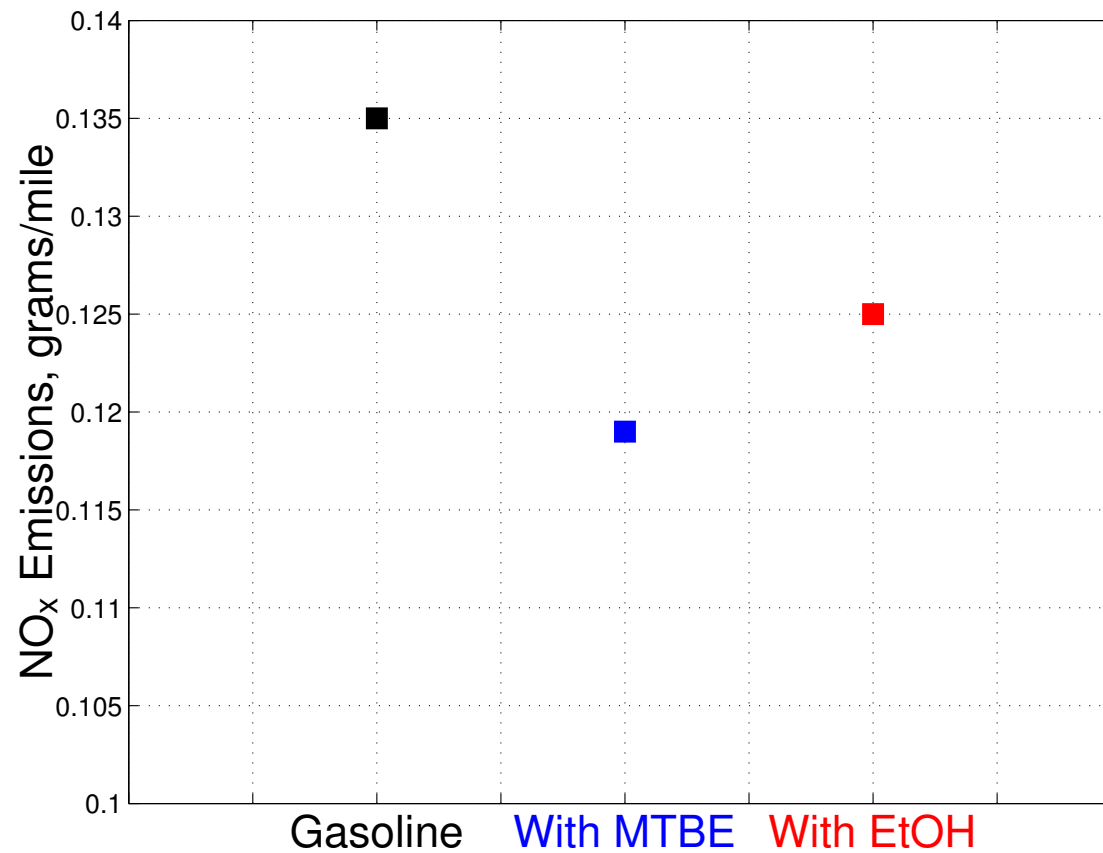
Source: CAL HODGE, President of A 2nd Opinion, Inc.

6-Fold Increase of VOC...



Source: CAL HODGE, President of **A 2nd Opinion, Inc.**

5%-Higher NO_x...



Source: CAL HODGE, President of **A 2nd Opinion, Inc.**

And the Winners Are...

- ⑥ ARCHER DANIEL MIDLANDS CO.
- ⑥ CARGILL, INC.
- ⑥ A. E. STANLEY

And The Loser Is...

