Ethanol from Corn: Just How Unsustainable Is It?

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- 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. . .

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

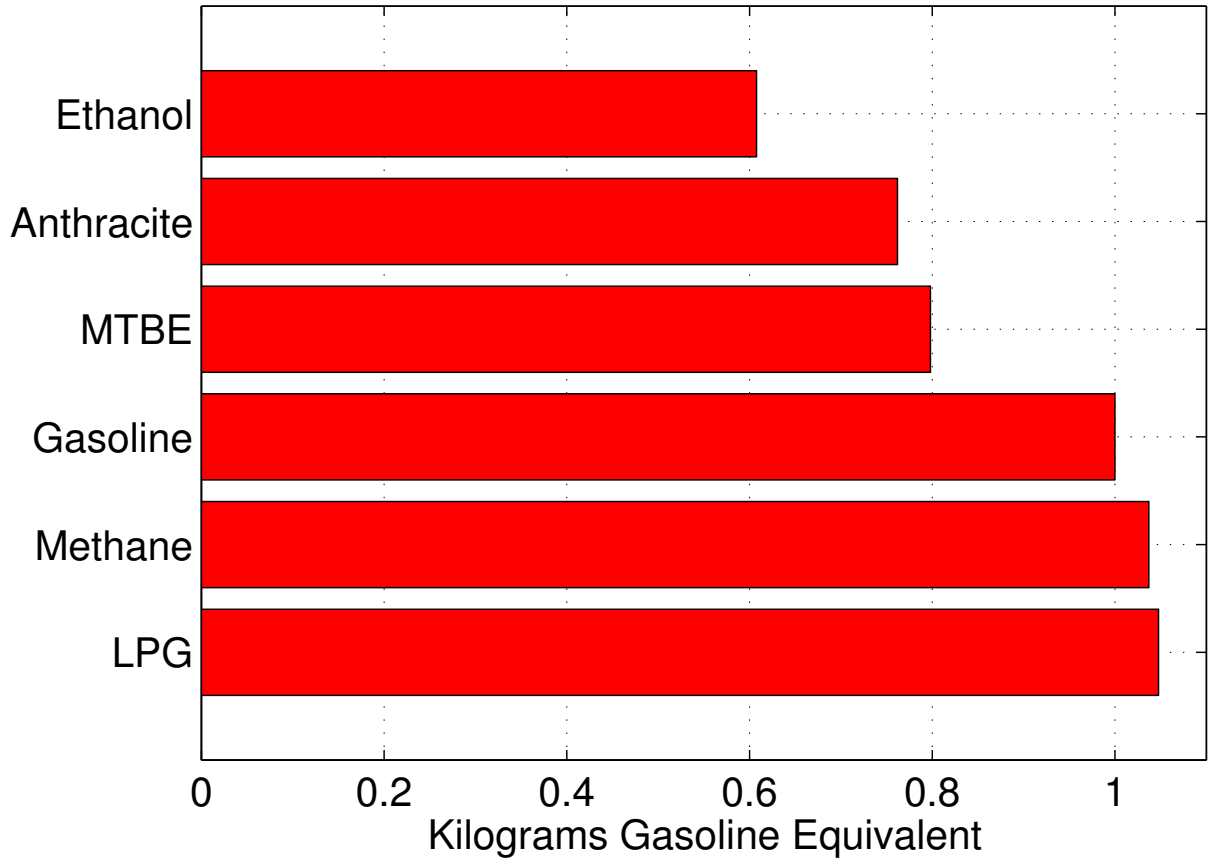
Ethanol From Corn. . .

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

Ethanol From Corn. . .

- The process complexity turns-off the public and politicians
- 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
- One should continue filtering out errors in reporting and disinformation

Fuel Energy Contents...



1 gallon of ethanol = 0.65 gallons of gasoline

Talk Outline. . .

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

Energy Inputs to Corn Production...

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

1 Bushel of Corn Is. . .

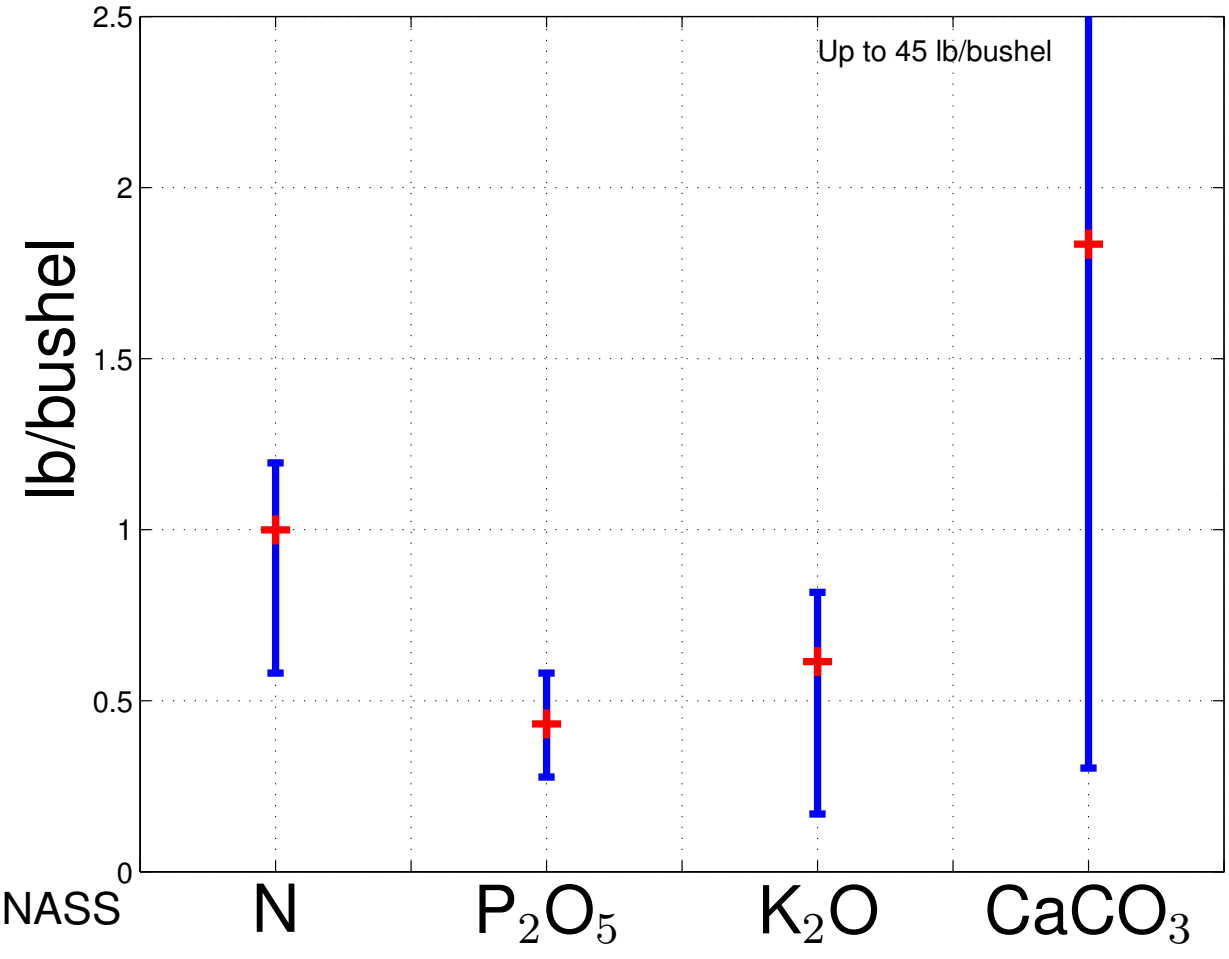


25.4 kg or 56 pounds of corn kernels with 15% moisture content $\sim$8 gallons

1 Bushel Takes 32 m^2 . . .



Fertilizer Uptake Per Bushel. . .



1997 USDA-NASS

Nitrogen Fertilizer. . .

- Is produced exclusively from **natural gas**
- Its production requires twice as much energy as steel
- Energy required to produce different nitrogen fertilizers must be expressed relative to the content of elemental nitrogen, N
- All fertilizers must be transported, the most popular ones must be granulated
- 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

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

Forms of Nitrogen Fertilizer...

Ammonia, NH_3 (82% N):

- 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, $CO(NH_2)_2$ (45% N):

- Obtained from NH_3 and CO_2: $2NH_3+CO_2 \rightarrow CO(NH_2)_2+H_2O$
- 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):

- Is obtained from nitric acid HNO_3 and ammonia NH_3: $NH_3 + HNO_3 \rightarrow NH_4NO_3$
- Nitric acid is obtained by burning ammonia over catalysts to produce NO_x
- Total energy per 1 lb of N is

  "30 Years Old" Ammonia $+ 4$GJ/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

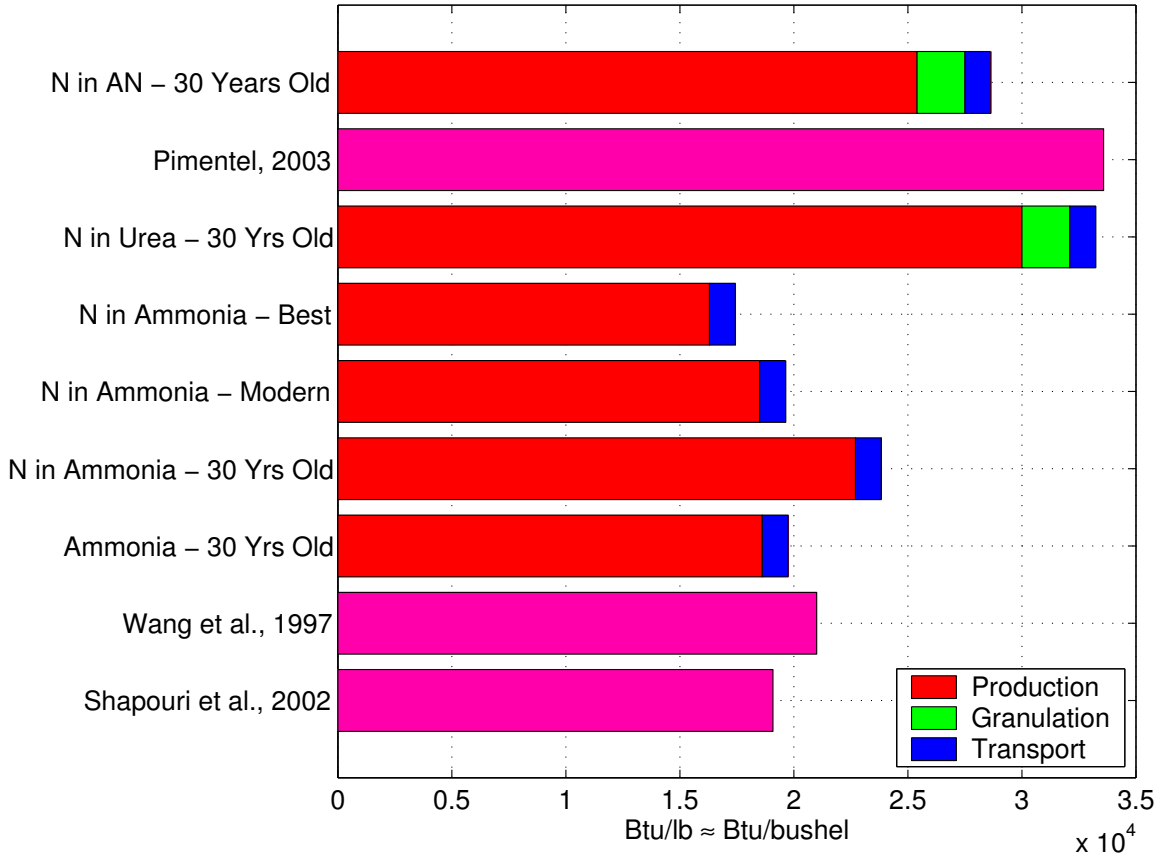
Other Nitrogen Fertilizer Costs. . .

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

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

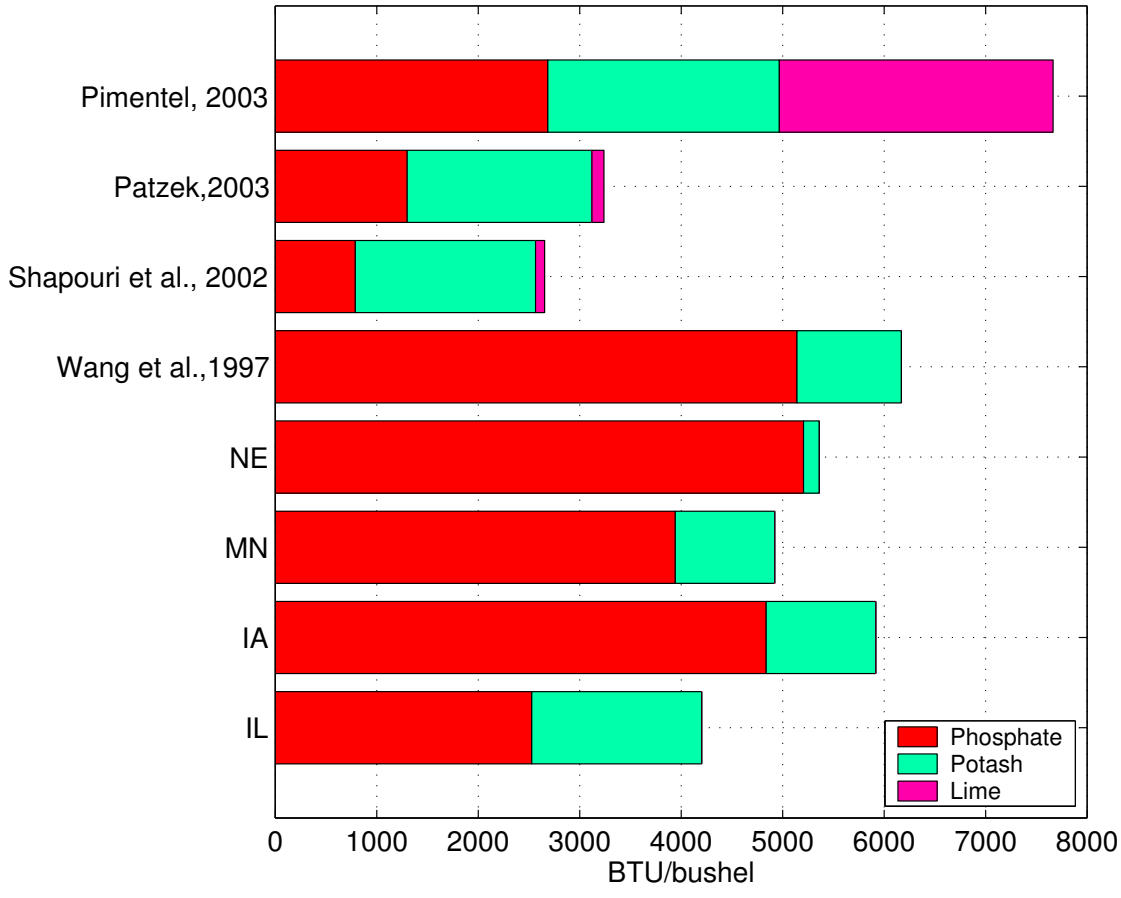
- Total energy consumption is

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

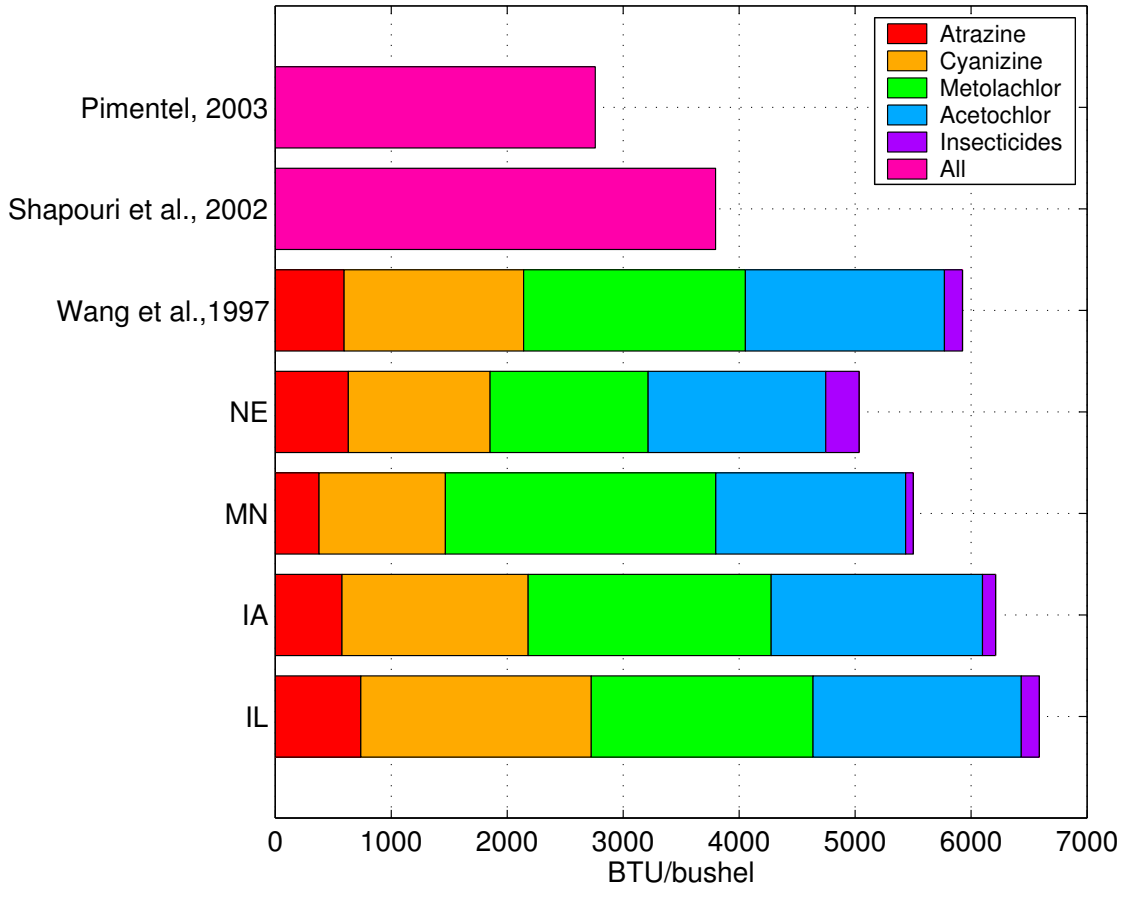
Source: Energy and Environmental Profile of the U.S. Mining Industry, Vol 9, *Limestone & Crushed Rock*, U.S. DOE, 2002

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

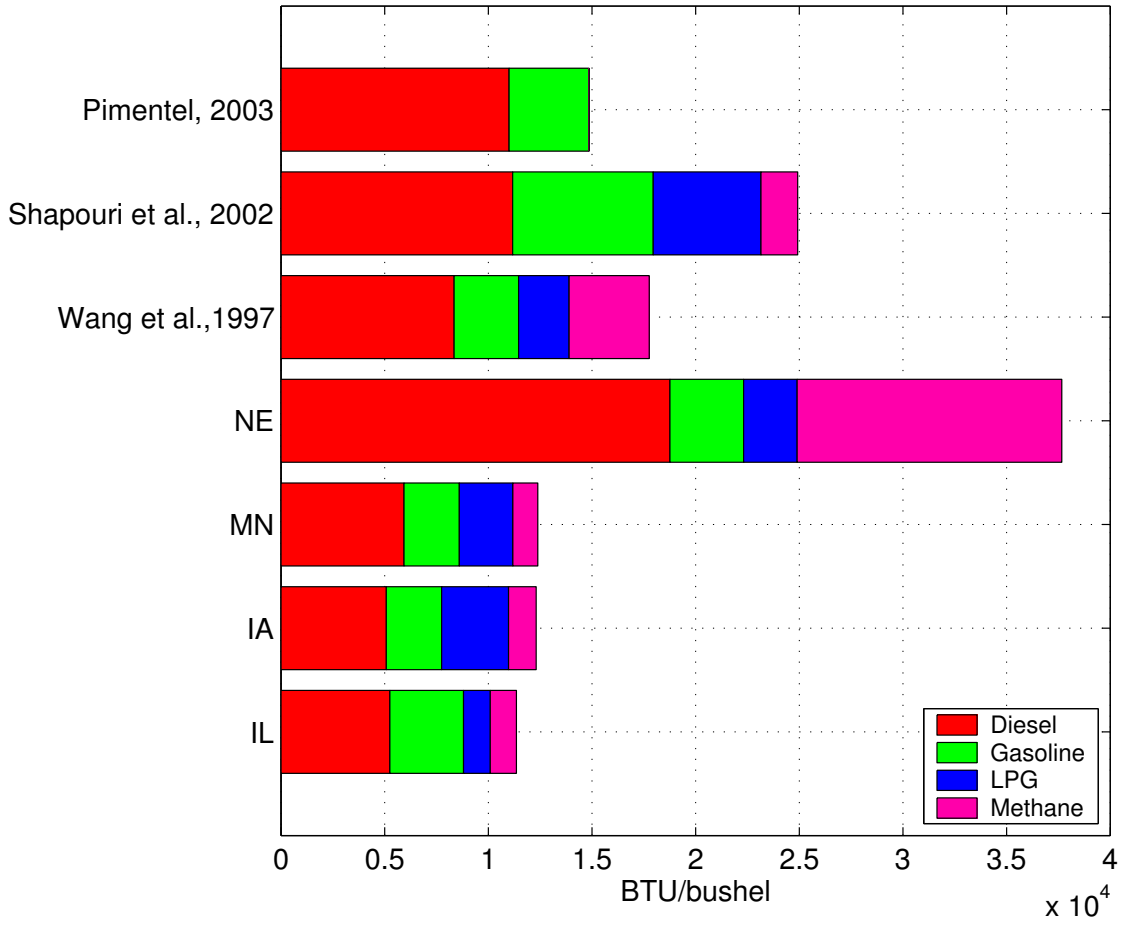
Energy in P, K, Ca. . .



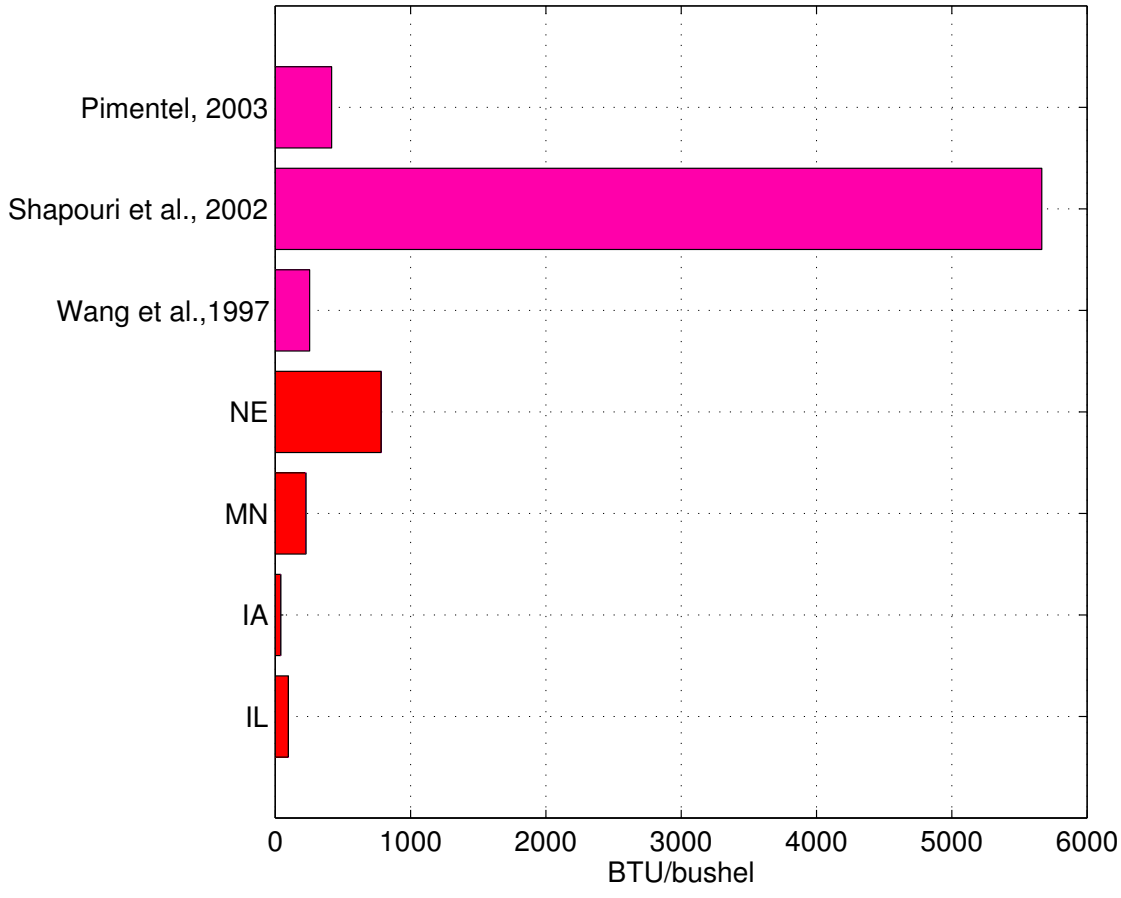
Energy in Herbicides/Insecticides. . .



Fossil Fuel Energy in Corn. . .



Energy in Electricity. . .



Energy in Corn Seeds. . .

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

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

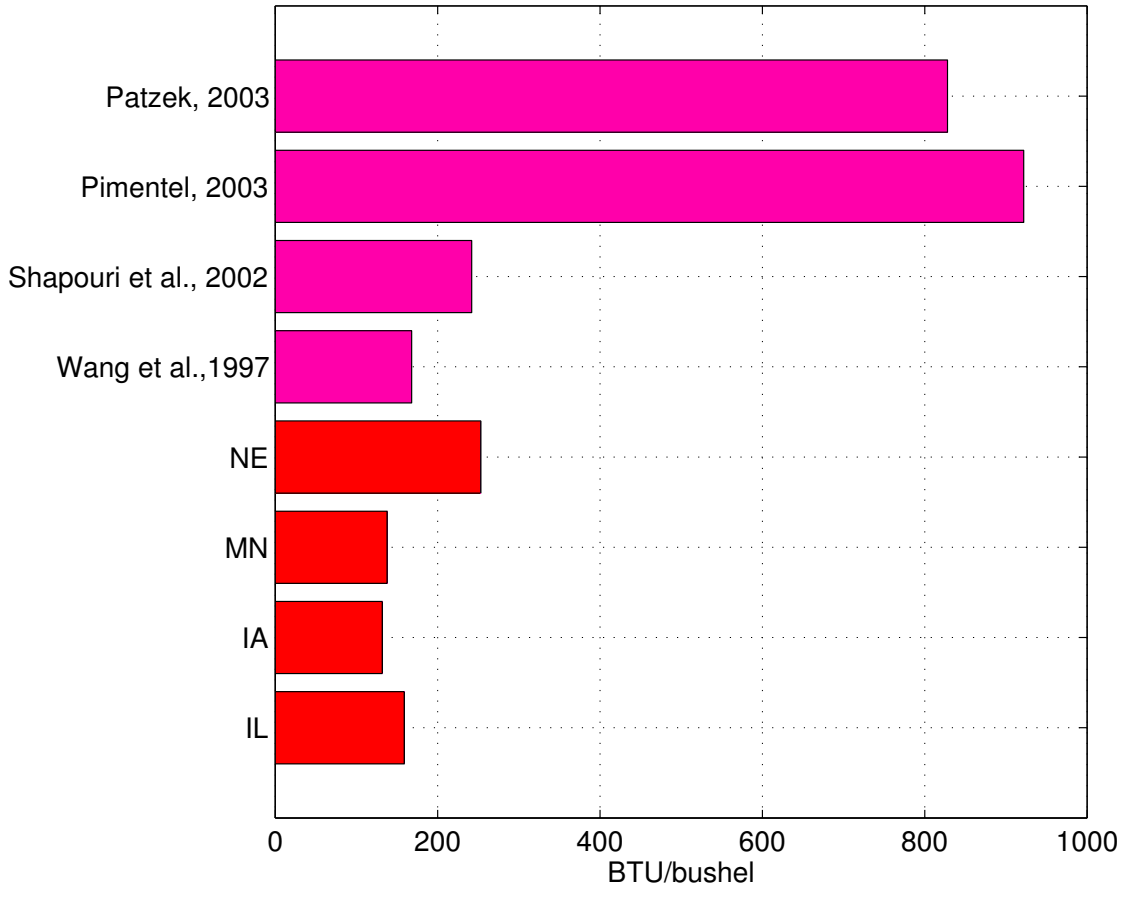
Source: *Corn Chemistry and Technology*, AACC, 2003

Energy in Corn Seeds. . .

Bottom line:

- I have used the lowest seed grain density of 23,000 kernels/acre
- PIMENTEL (2003) and SHAPOURI *et al.*. (2002) used 25,500 kernels/acre
- 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...

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

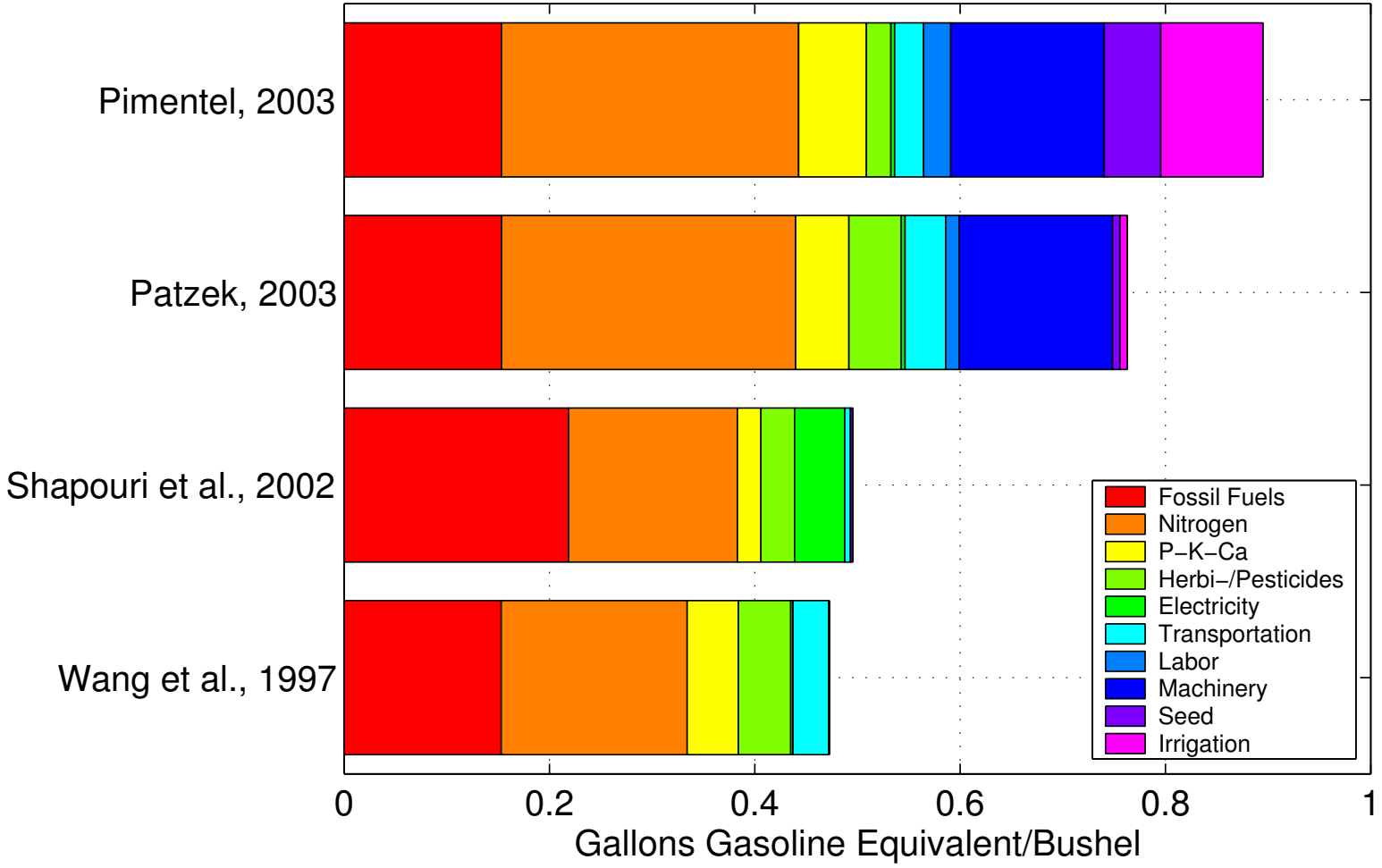
$$0.081\ \text{m} \times 10{,}000 \frac{\text{m}^2}{\text{ha}} \times 0.4047 \frac{\text{ha}}{\text{acre}} \times 1000 \frac{\text{kg}}{\text{m}^3} \times$$
$$\times\ 100\ \text{m} \times 9.81 \frac{\text{m}}{\text{s}^2} / 0.75 = 4.2877 \times 10^7\ \text{J/acre}$$
$$= 308\ \text{Btu/bushel}$$

Energy in Labor. . .

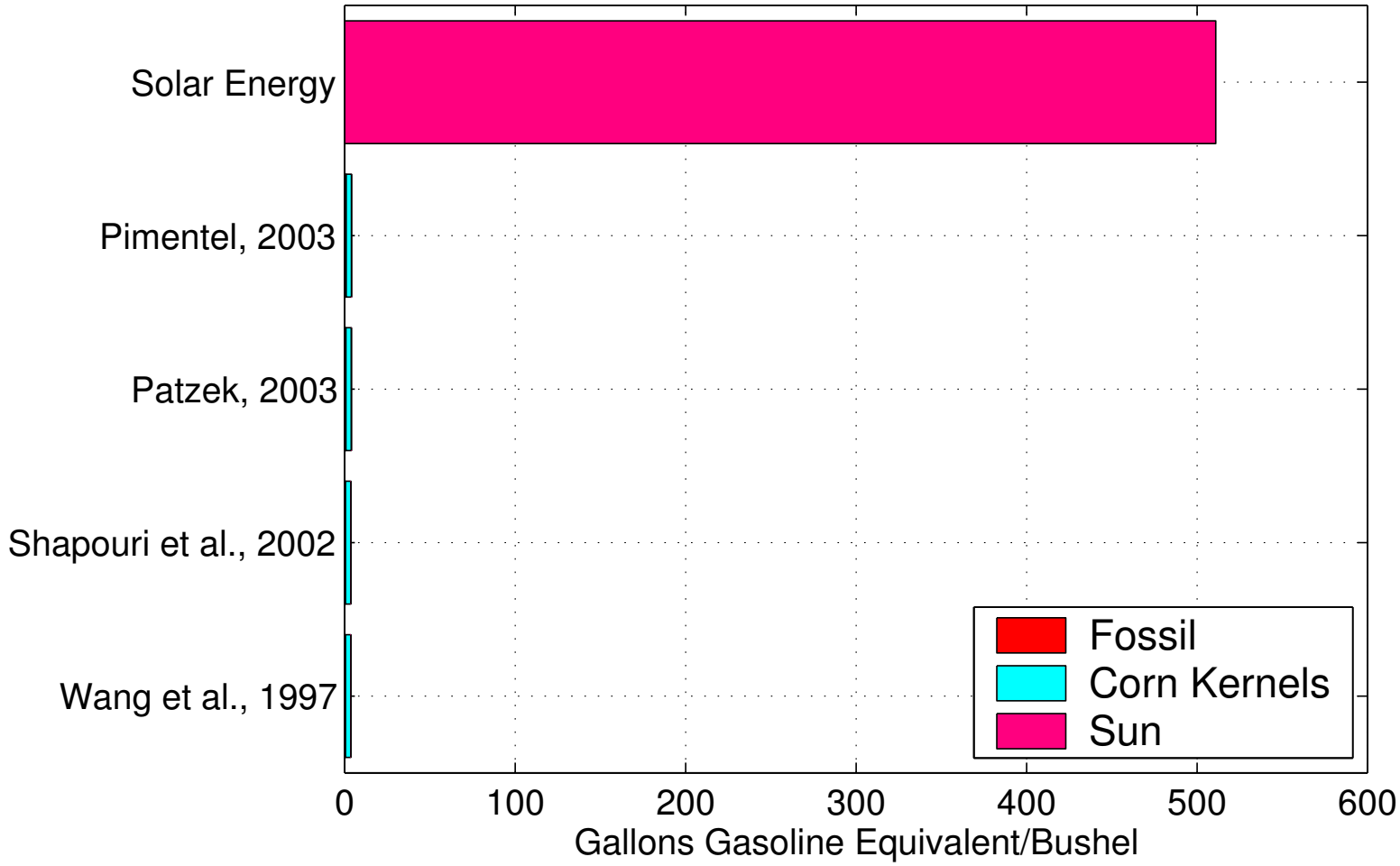
- Labor time is 6.2 hrs/day/ha in a growth season of 120 days (USDA-NASS, 1999)
- A physical worker is on 4,000 kcal/day diet
- Crop yield is 132 bushels/acre

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

Fossil Energy Inputs into Corn. . .



Solar Energy Input into Corn. . .



Summary of Energy Inputs. . .

- 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)

- PIMENTEL (2003) seems to overestimate the energy content of corn seeds, and the energy cost of irrigation

Summary of Energy Inputs. . .

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

Corn to Ethanol. . .

Corn Kernels	$\rightarrow$	Starch	$\rightarrow$
Steeping		Gluten	
Grinding		Liquefaction	
Germ Separation		Saccharification	

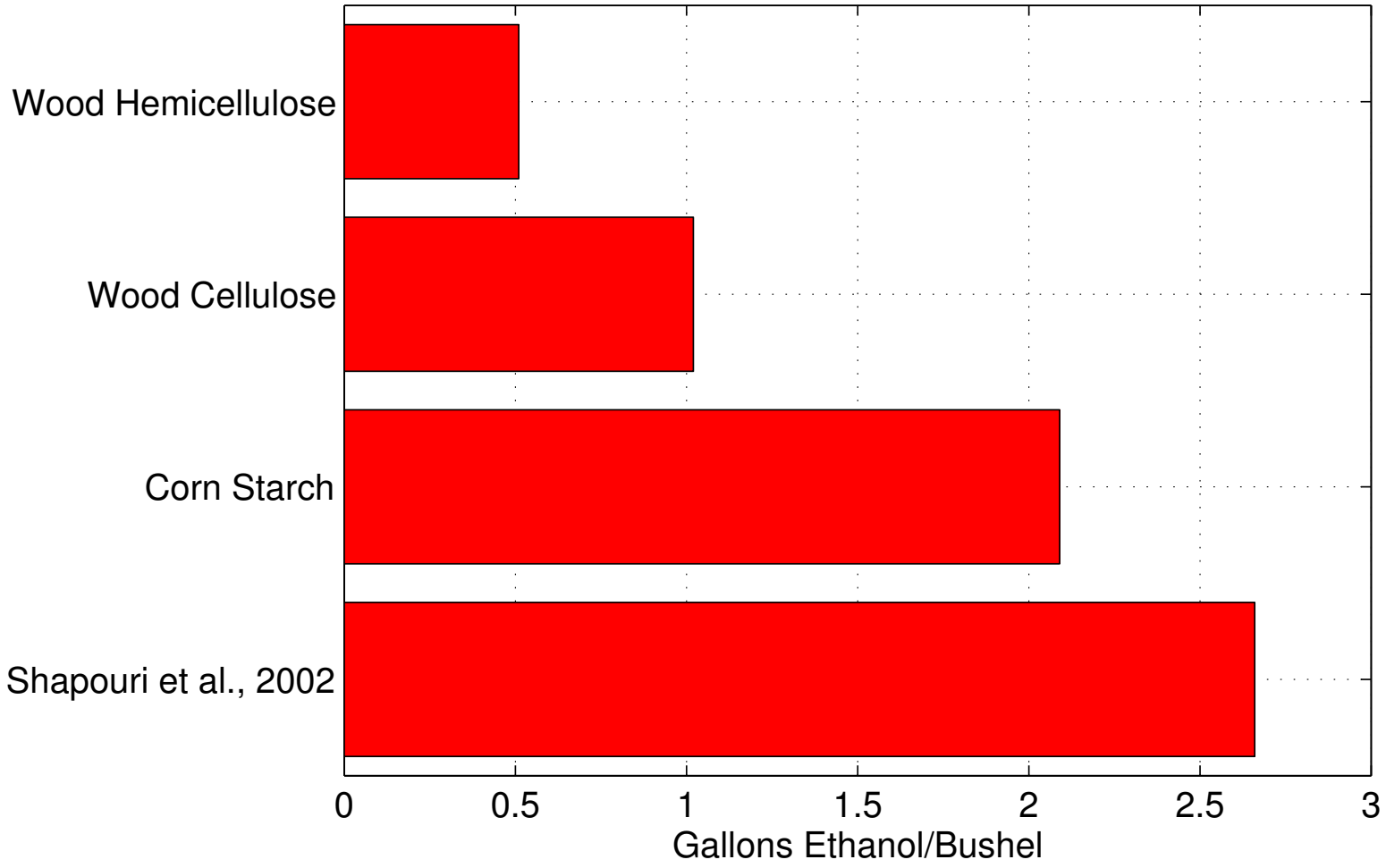
Glucose	$\rightarrow$	Ethanol
Fermentation		Distillation
CO_2		Dehydration

$(CH_2O)_6 \rightarrow 2C_2H_5OH + 2CO_2$ 1/2 glucose goes to CO_2

Accounting Problems. . .

- 66-68% of wet-milled corn kernels is starch
- Starch is hydrolized and converted to glucose with 90-100% efficiency
- Glucose is fermented to industrial beer with 51% efficiency (chemistry) and yield efficiency of 77-88%
- Beer is distilled and dewatered with 100% efficiency
- 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. . .

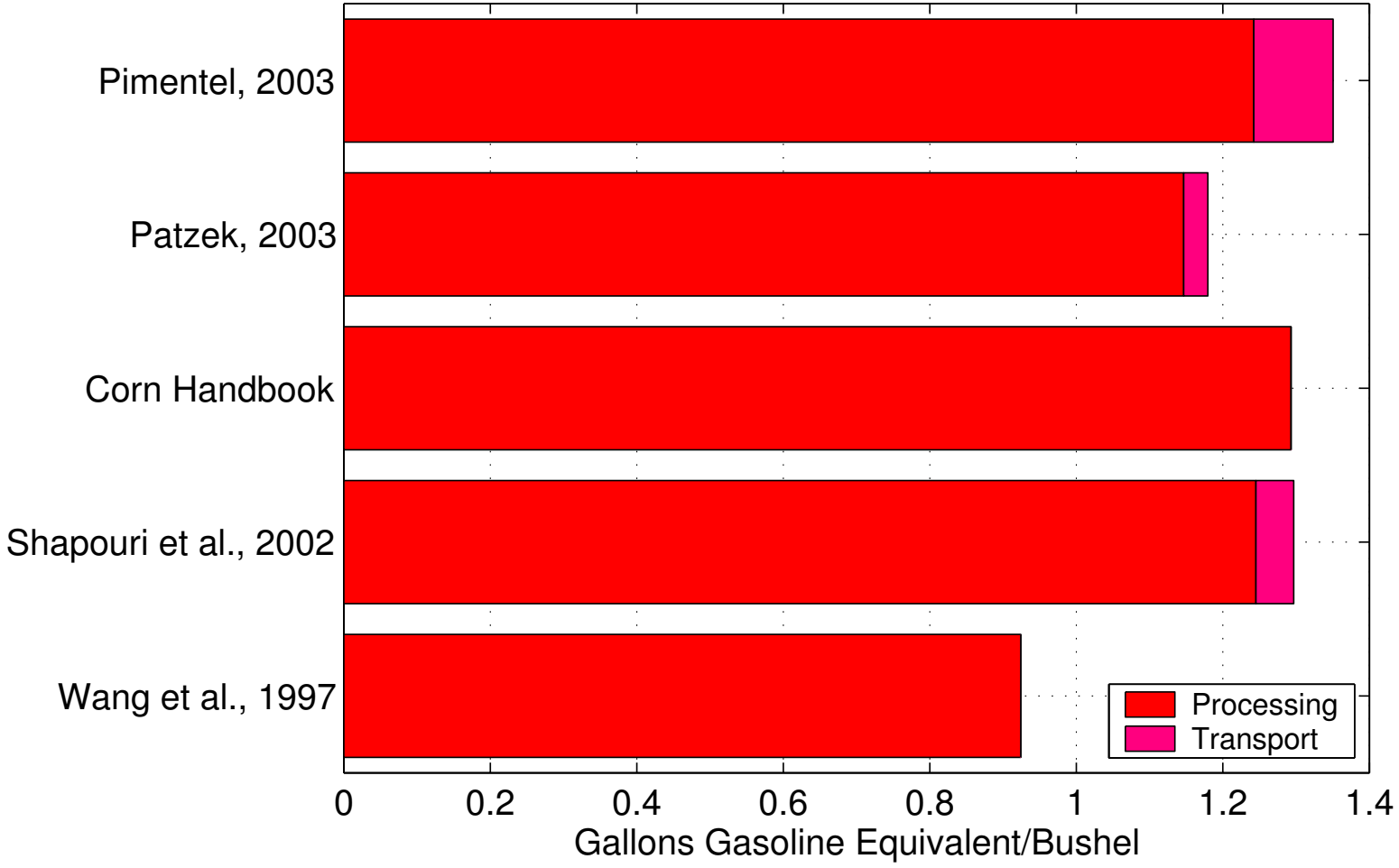


For Sale: Tucumcari Plant. . .



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

Energy Inputs to Ethanol. . .



Raw Corn Products. . .

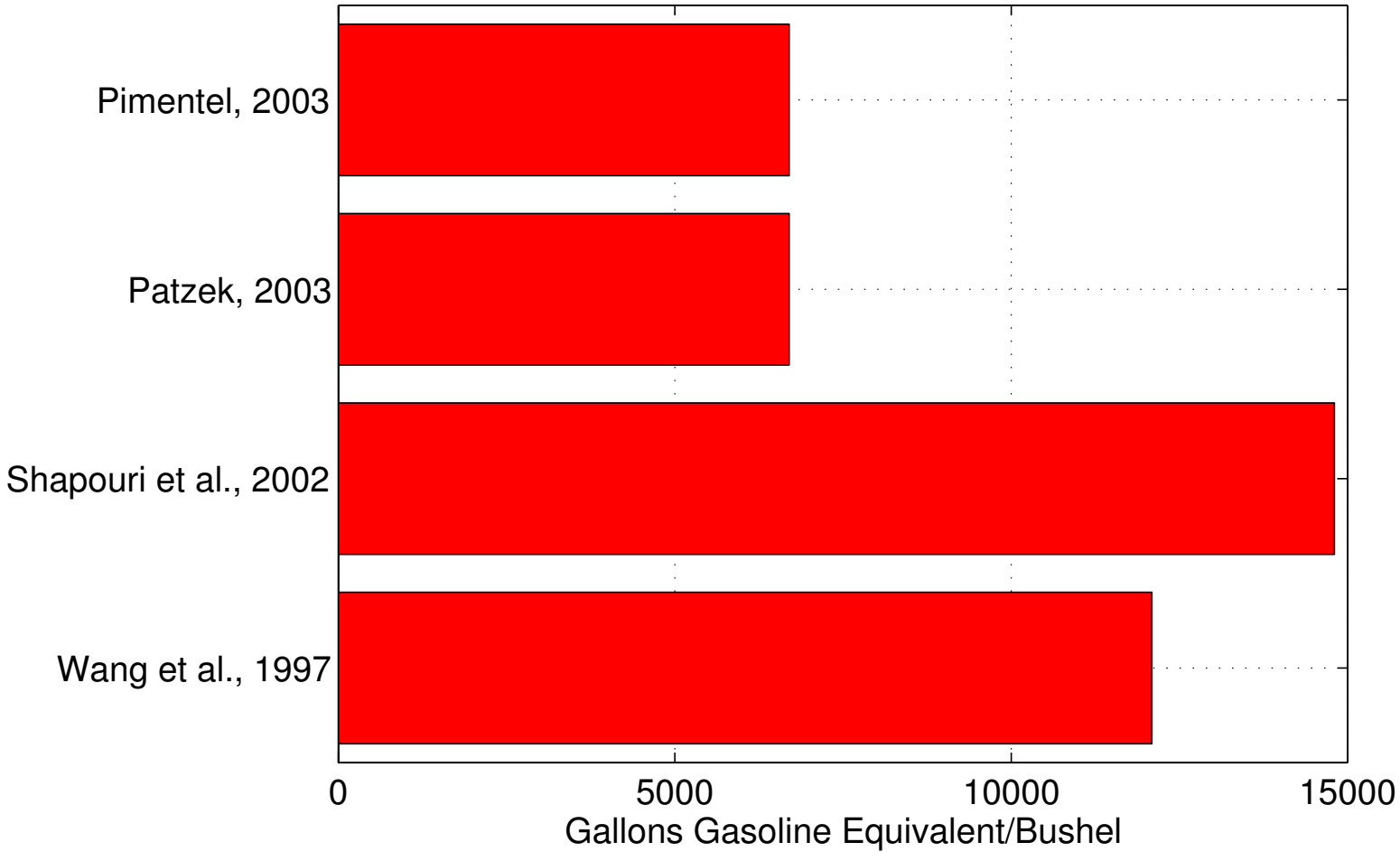
On dry mass basis:

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

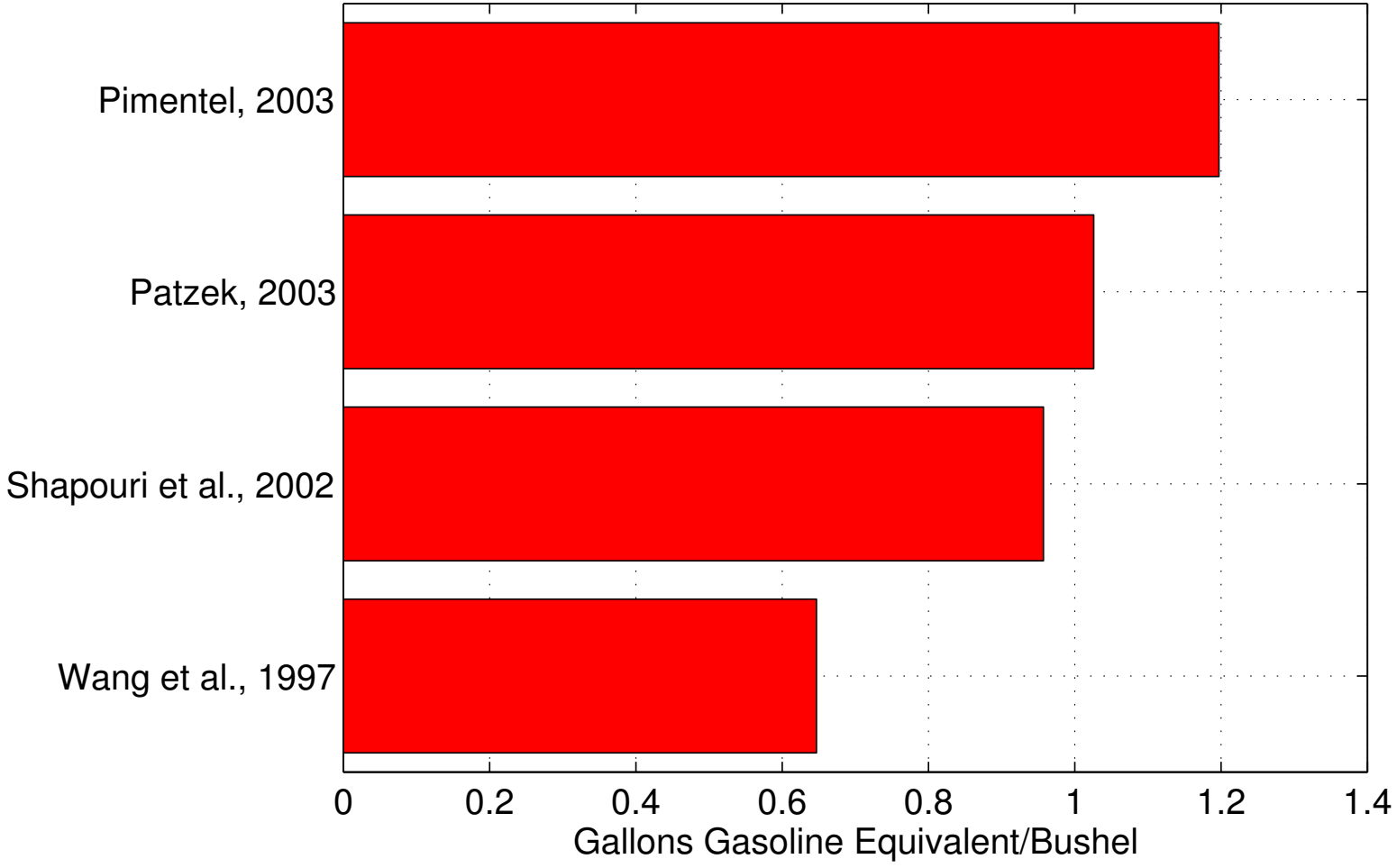
Energy Credits. . .

- WANG *et al.*, 30% of energy inputs (10-year average market value)
- SHAPOURI *et al.*, 14,804 Btu/gal of ethanol (replacement of soybean meal with corn gluten feed and meal)
- 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)

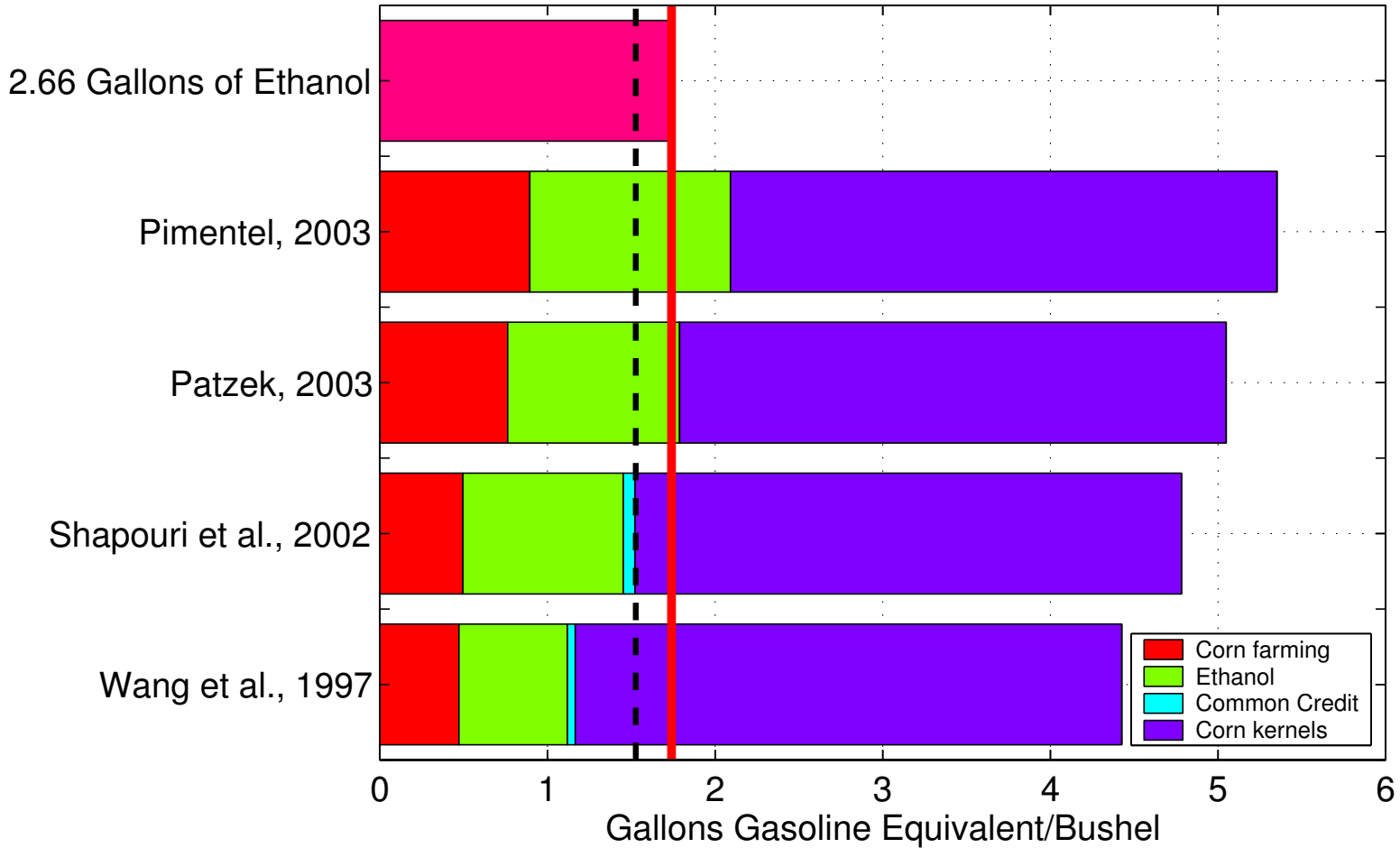
Energy Credits to Ethanol. . .



Net Energy Inputs to Ethanol. . .



Overall Energy Balance. . .



Bottom Line. . .

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

- 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
- The estimates by SHAPOURI *et al.* (2002) are in some ways more accurate than those by WANG *et al.* (1997), but still too low
- My estimates agree most with those by PIMENTEL (2003)

How Much Water?

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

- 38-45 liters (10-12 gal) for corn fractionation (p. 450)
- 75-95 liters (20-25 gal) in fermentation (p. 697)
- 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*:

- A wet milling plant can generate as much waste as a medium-size city (p. 470)
- 5-day BOD of waste water is 1,000-2,000 mg/L
- Waste content is 0.35 lb BOD_5/bushel

Court Settlement. . .

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

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

CAT LAZAROFF - ENS, 3 Oct 2002

So What Have We Achieved?

We have

- Burned more fossil fuels than the energy content of the ethanol from corn
- Degraded and eroded soil on millions of acres
- Polluted surface and groundwater with nitrates, herbicides, pesticides, and ethanol waste
- Polluted air with CO, NO_x, SO_2, VOC, *etc.*
- Continued to waste $ billions of taxpayers' money
- Devised a terrible solution of air quality problems

Federal Ethanol Subsidies. . .

- U.S. pays its corn farmers $10 billion a year in subsidies (8.6% cropland for ethanol)
- Federal excise taxes per gallon of fuel: $0.184 for gasoline and $0.132 for EtOH-10 (10 vol% ethanol)
- 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. . .

- 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
- 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

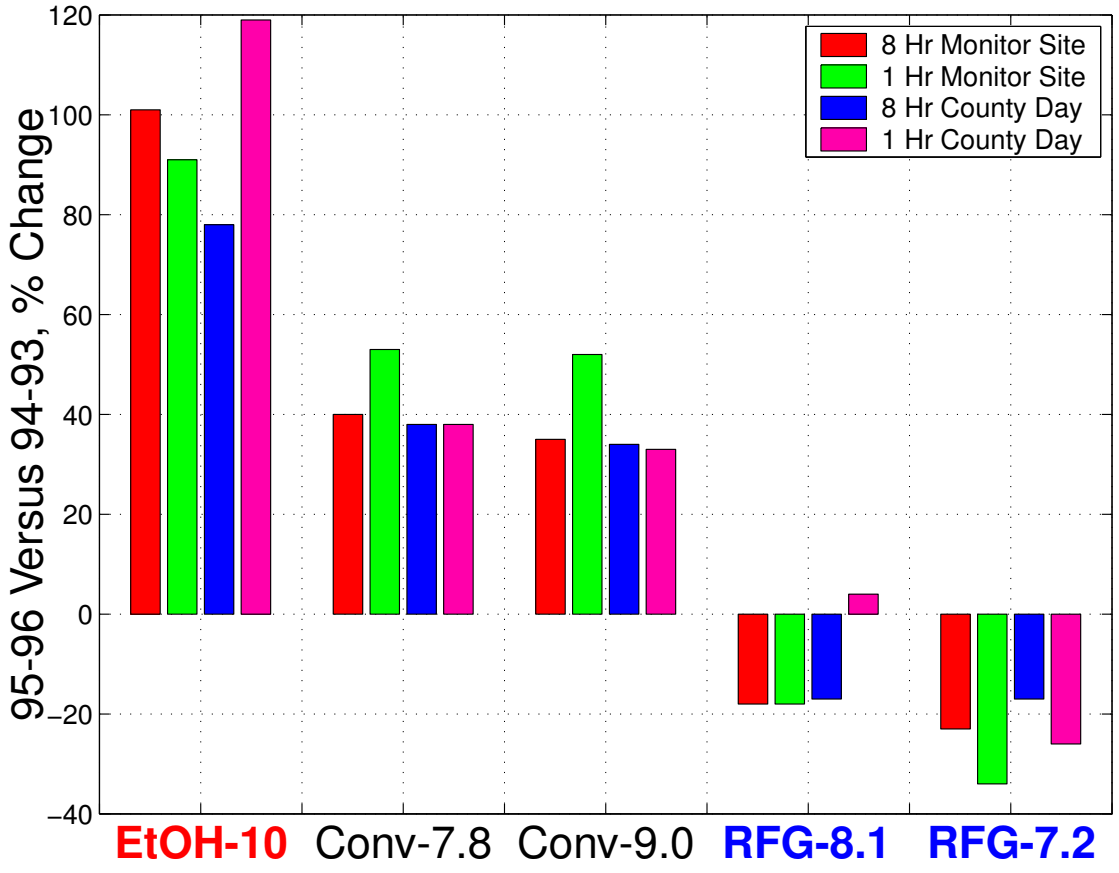
GGE = Gallons of Gasoline Equivalent

Unsafe Experiment?. . .

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

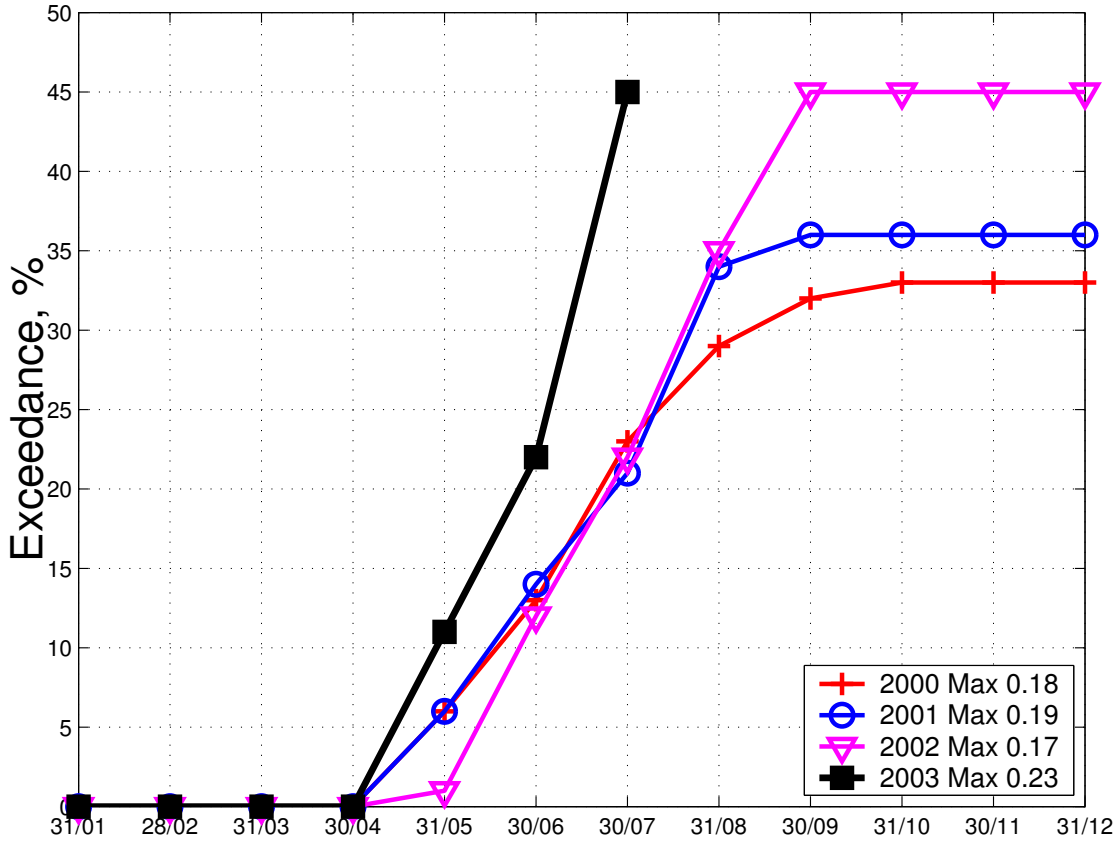
- Over 70% of gasoline produced in Southern California has switched from MTBE to ethanol
- The Federal ozone level exceedances in Southern California have jumped up
- 10 vol% ethanol blends have a 70-point poorer driveability index than MTBE or hydrocarbon blends
- EtOH-10 gasoline blends have 6 times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

Higher Ozone Levels. . .



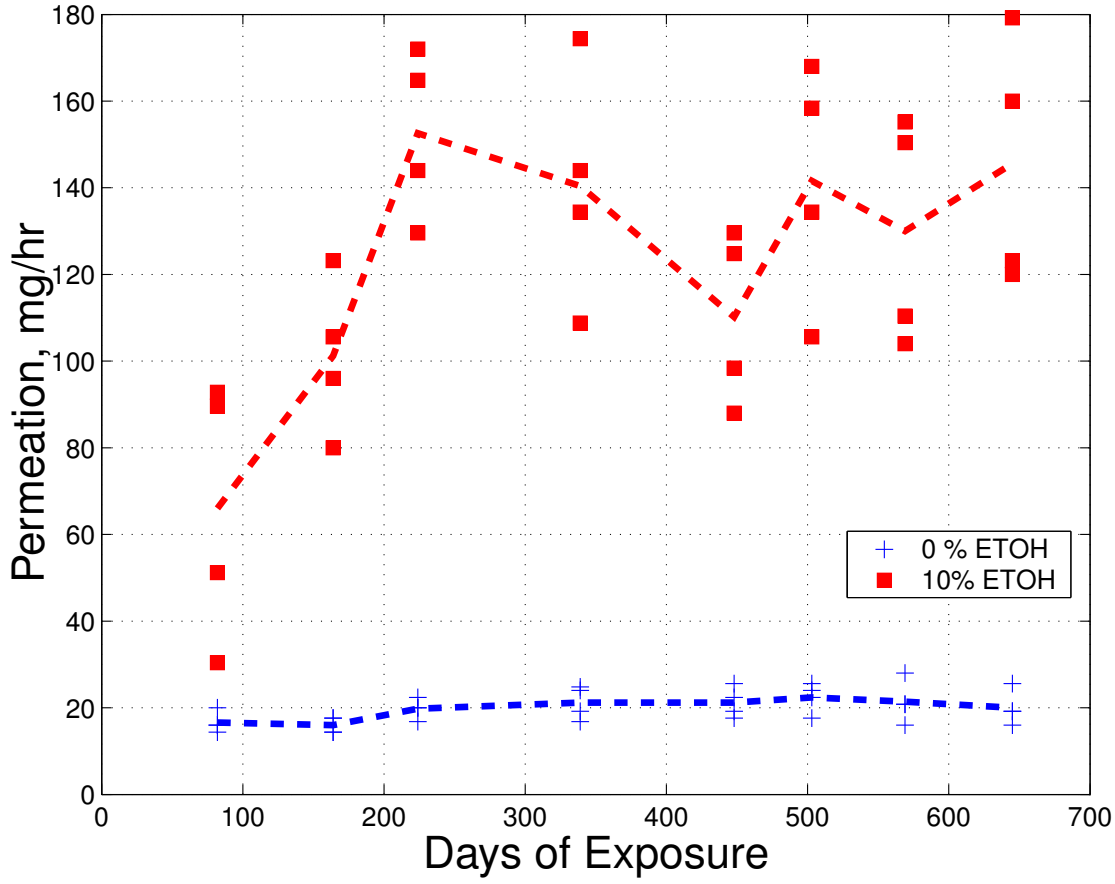
US-CA, Source: US EPA, CAL HODGE, President of **A 2nd Opinion, Inc.**

1-Hour Ozone Exceedance. . .



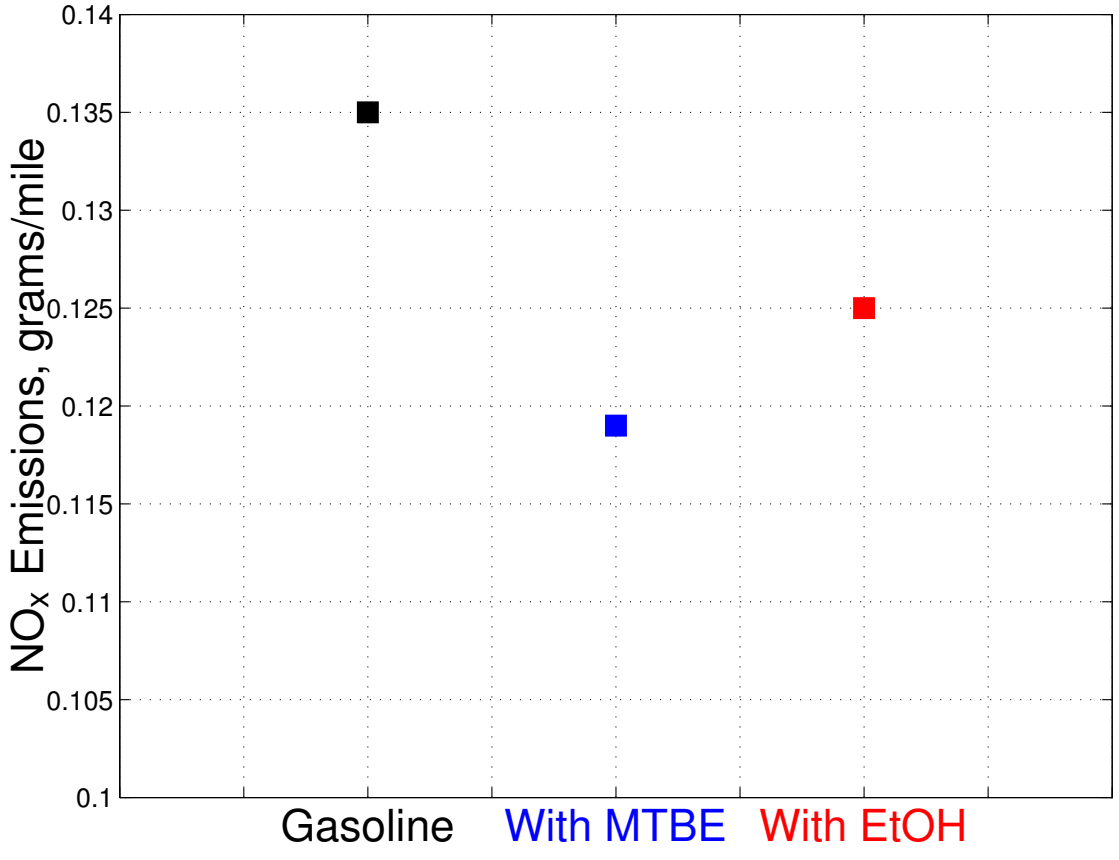
Source: CAL HODGE, President of **A 2nd Opinion, Inc.**

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. . .

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

And The Looser Is. . .

