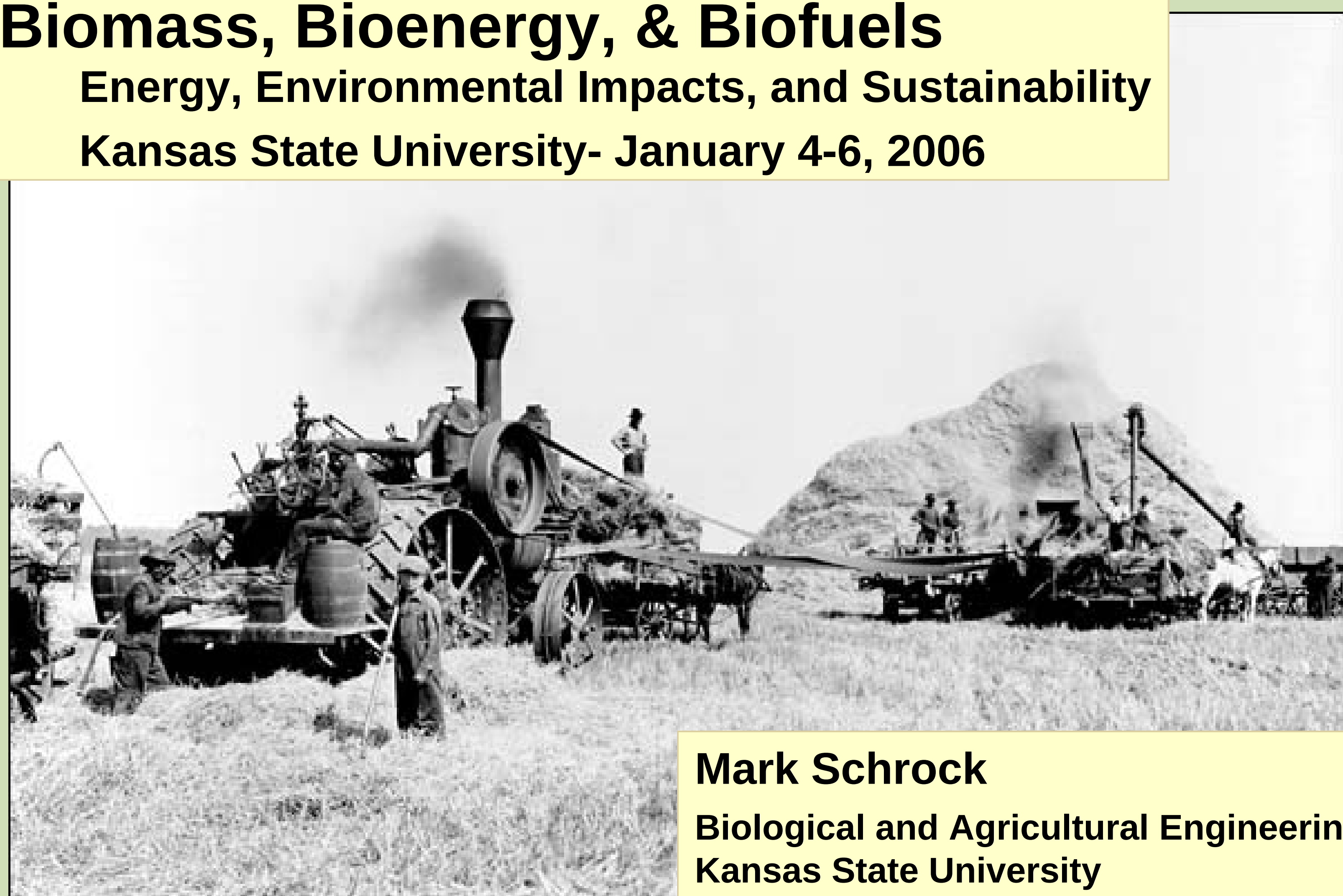
Biomass, Bioenergy, & Biofuels

Energy, Environmental Impacts, and Sustainability

Kansas State University- January 4-6, 2006



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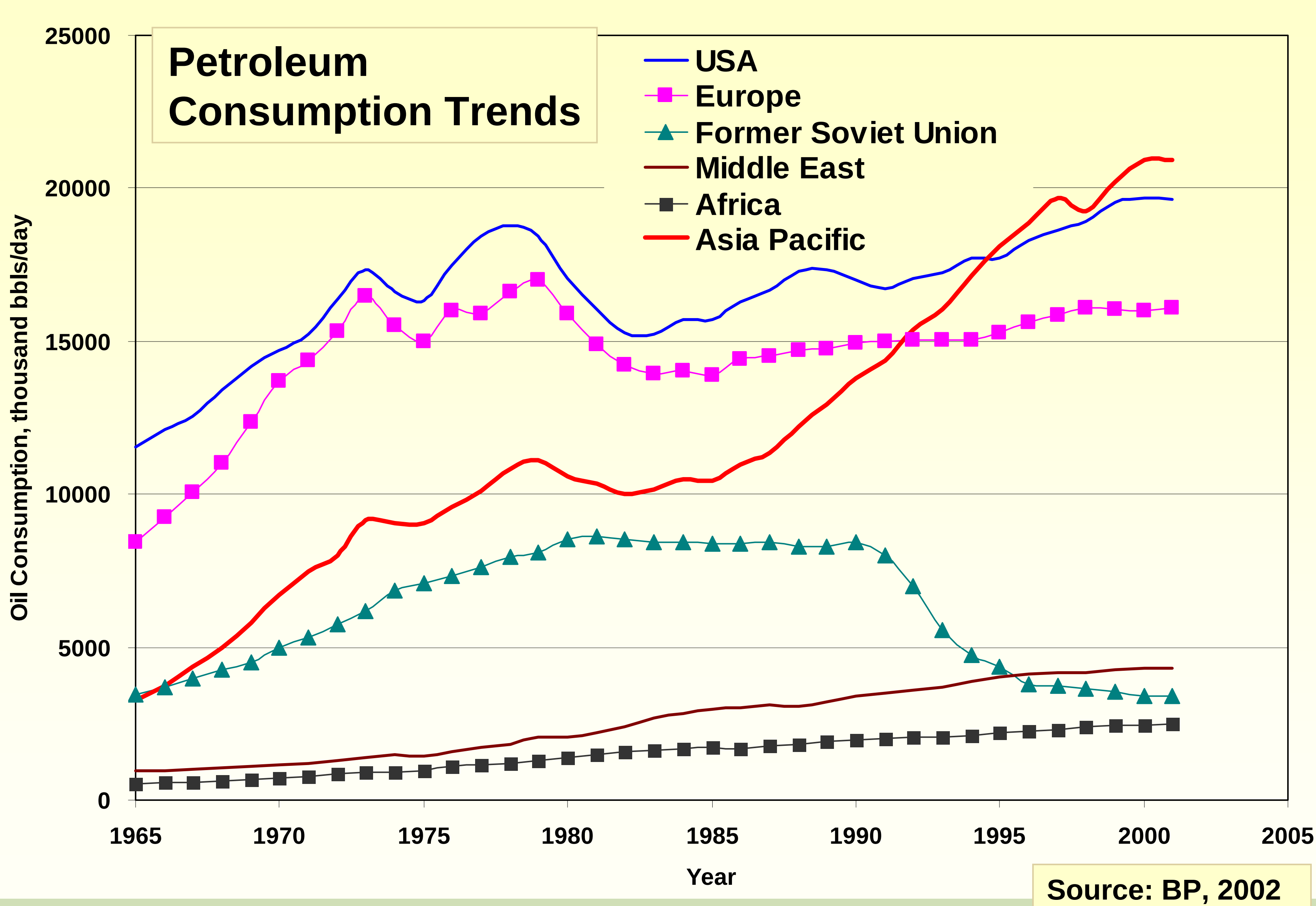
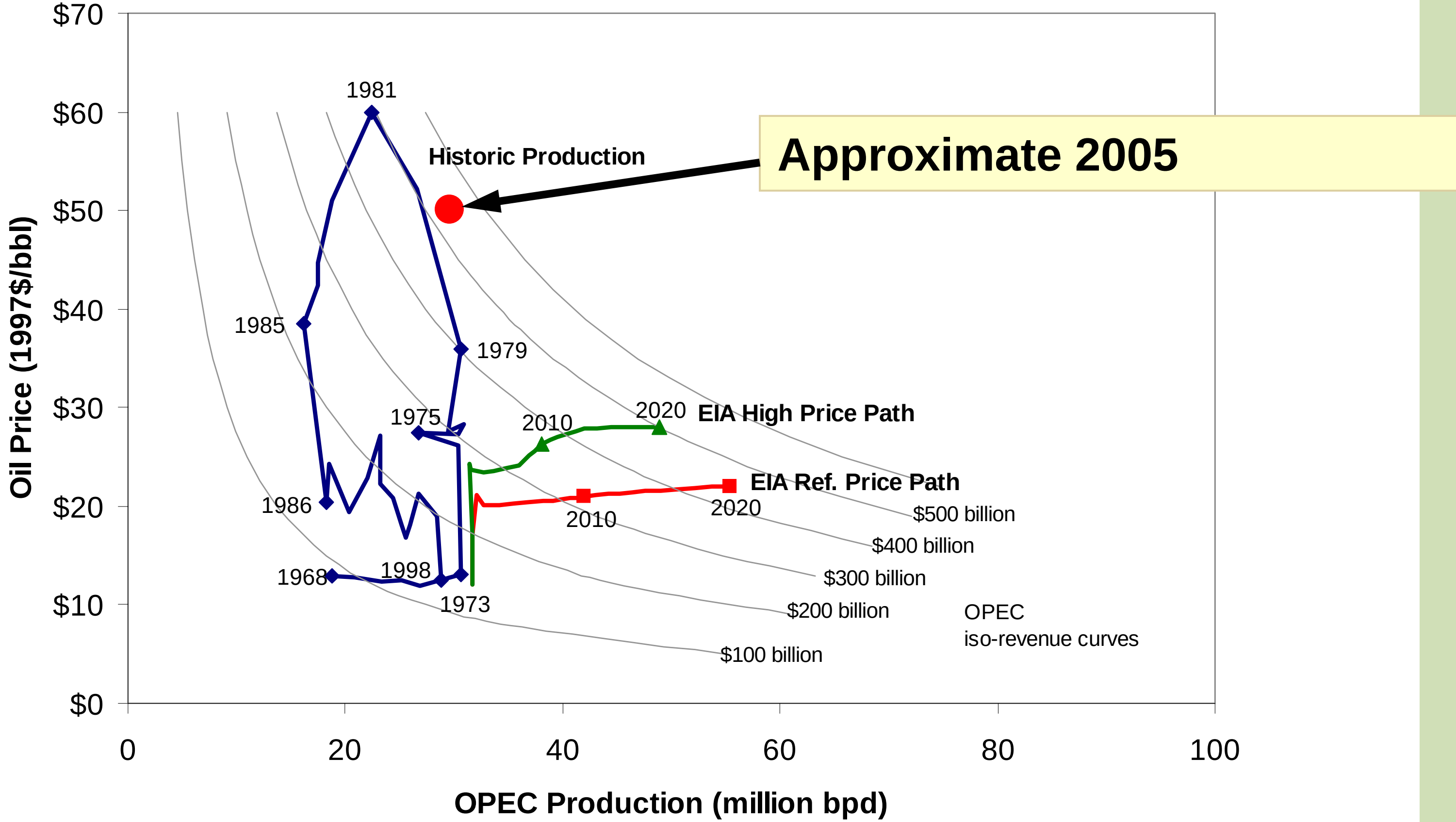


Petroleum Consumption Trends
USA
Europe
Former Soviet Union
Middle East
Africa
Asia Pacific
Oil Consumption, thousand bbls/day
25000
20000
15000
10000
5000
0
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Source: BP, 2002

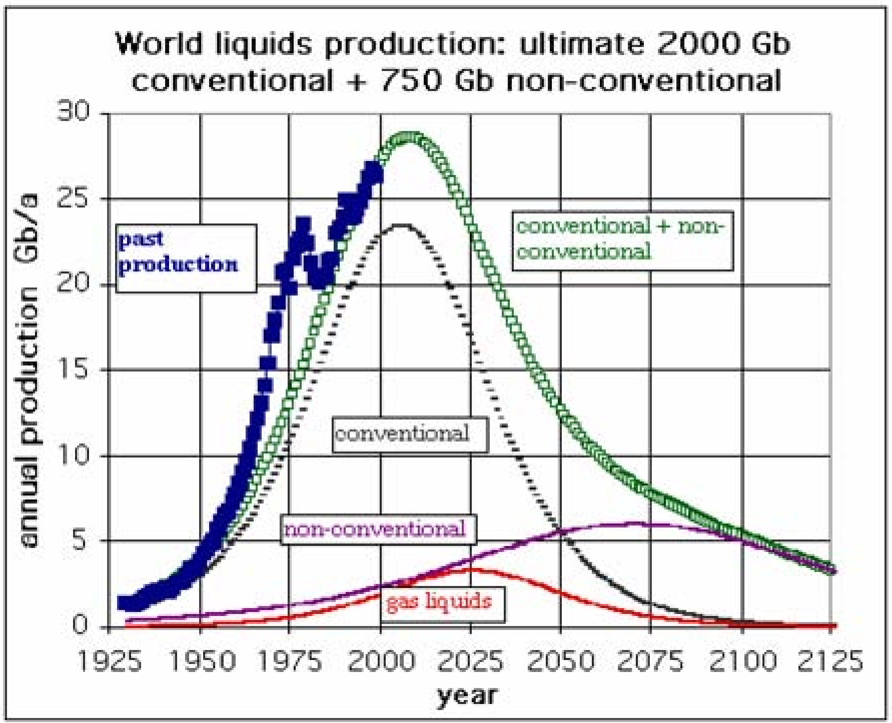
Oil Prices, OPEC Production and Revenue



“Global production of conventional oil will begin to decline sooner than most people think, probably within 10 years”

C.J. Campbell and J.H. Laherrere
Scientific American—March 1998

No One Really Knows...



“There’s plenty of cheap oil, says the US Geological Survey”

Eric Niiler
Scientific American—September 2000

Comparing the Energy Market to Agriculture

US Vehicle Fuel Consumption, 1999

	Billion Gallons
Gasoline	123
Diesel Fuel	33

Source: DOE

Agriculture's Energy Potential:

Energy contained in U.S. grain crops, total above-ground biomass.

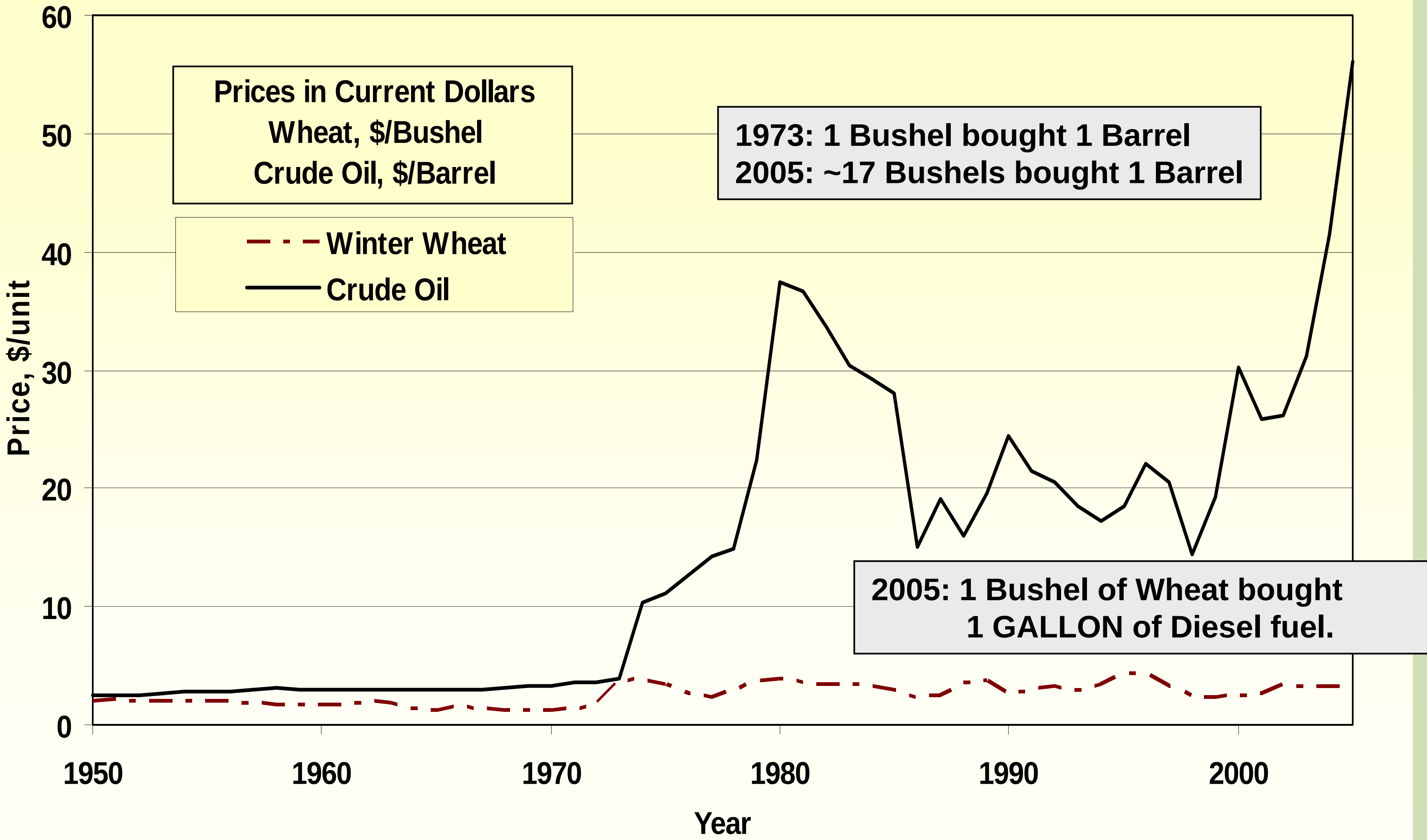
Grain	Record Bushels (Millions[1])	Year of Record	Grain Weight (lbs/bu)	Residue Weight (lbs/bu)	Above-Ground Biomass (MillionLbs)	Biomass Energy[2] (BillionBTU)	Biomass Energy Gasoline Equiv.[3] (BillionGal)
Corn	11,800	2004	56	56	1,321,600	9,912,000	85.4
Grain Sorghum	1,120	1985	56	56	125,440	940,800	8.1
Wheat	2,785	1981	60	100	445,600	3,342,000	28.8
Soybeans	3,120	2004	60	50	374,400	2,808,000	24.2
						Total	**146.5**

Notes: 1. USDA-NASS, 2. Assumed 7,500 BTU/lb, 3. Assumed 116,000 BTU/gal

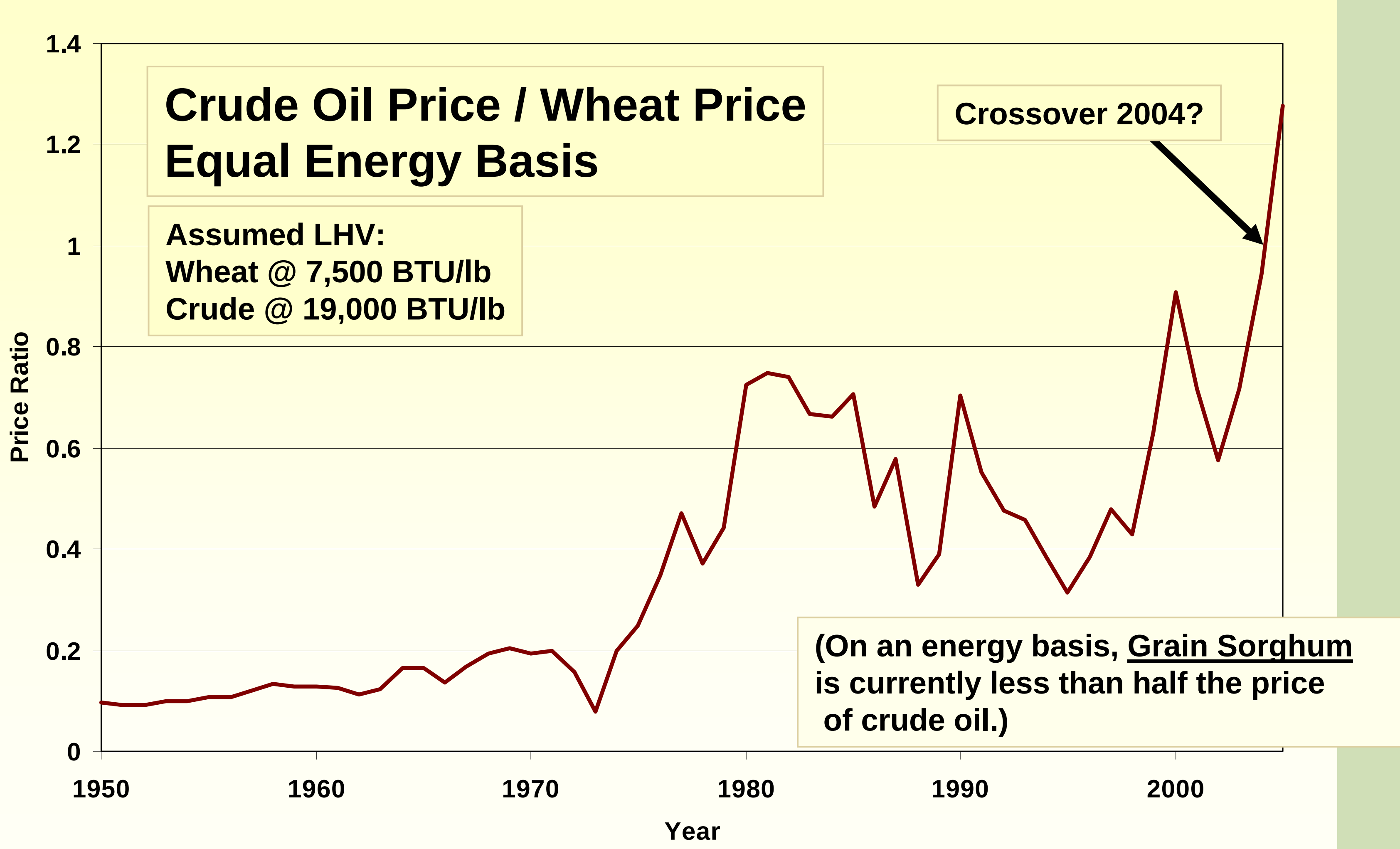
US Gasoline Consumption ~123 Billion Gallon

Conclusion: Energy is a MUCH larger market than food.

Relative Food and Energy Prices



Will Energy Put a Floor Under Grain Prices?



The Successor to Petroleum for Transportation has NOT been Identified

BioFuels (ETOH, Biodiesel, Methane)

PV or Wind>>Hydrogen>>Fuel Cell?

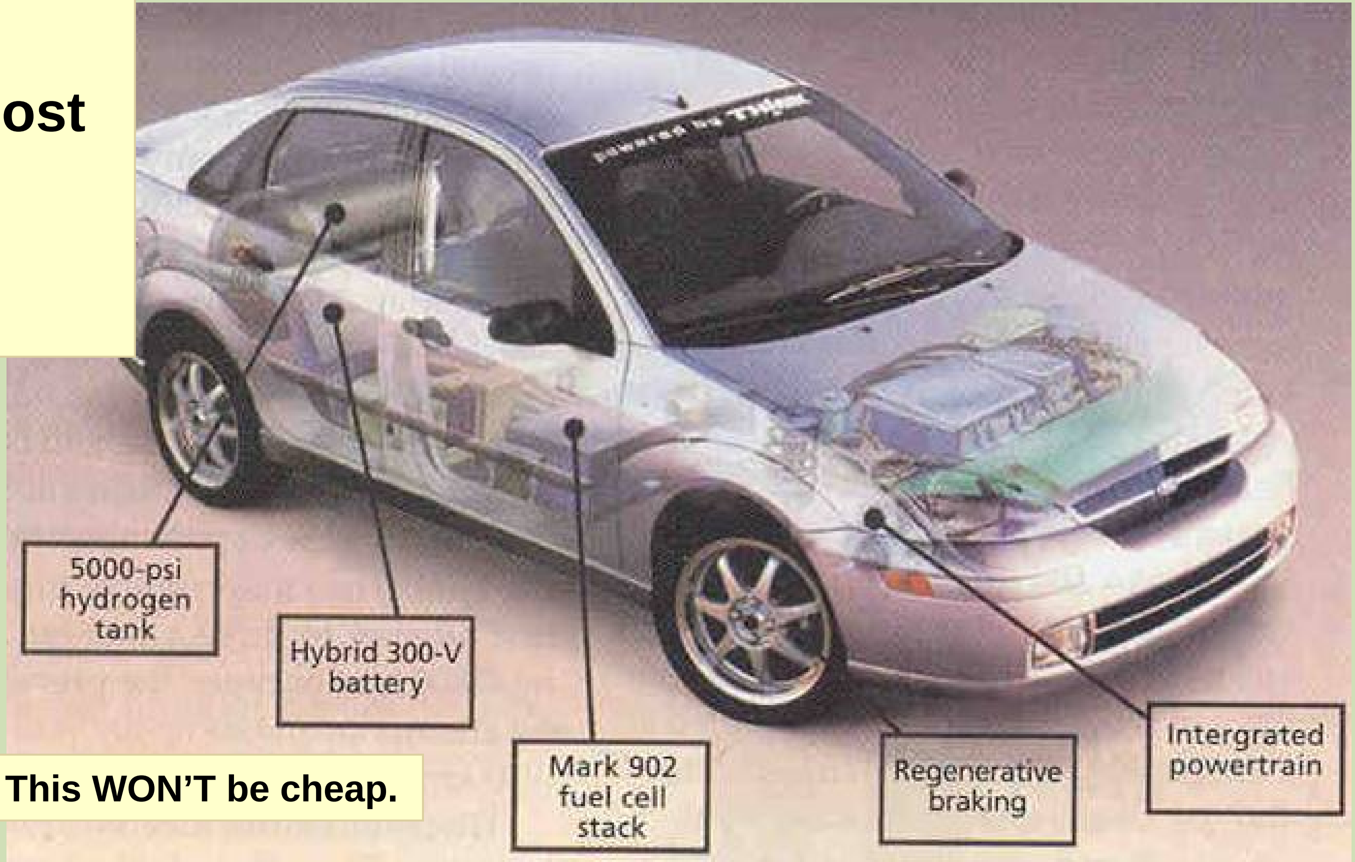
PV or Wind>>Batteries?

Coal-Derived Liquids>>IC Engine or Fuel Cell?

ALL Major Auto Makers (and DOE, USDA, etc) Have Active R & D…

Hydrogen Issues:

- Supply/Cost
- Storage
- Range
- Safety



Ford's new Focus FCV has been hybridized with the addition of a 300-V Sanyo battery pack and a Continental Teves regenerative brake-by-wire system.

MDS Prediction: This WON'T be cheap.

Moving Transportation Beyond Petroleum

Conserve
Change Transportation Mode Mix
Transition to Renewables

1949

1964

1973

Current

2005: Class 8 Trucks Burn ~ ½ of US Diesel fuel

Comparing Transportation Modes

Current Fuel:

- Diesel
- Electricity
- Coal
- Wood

Future Fuel:

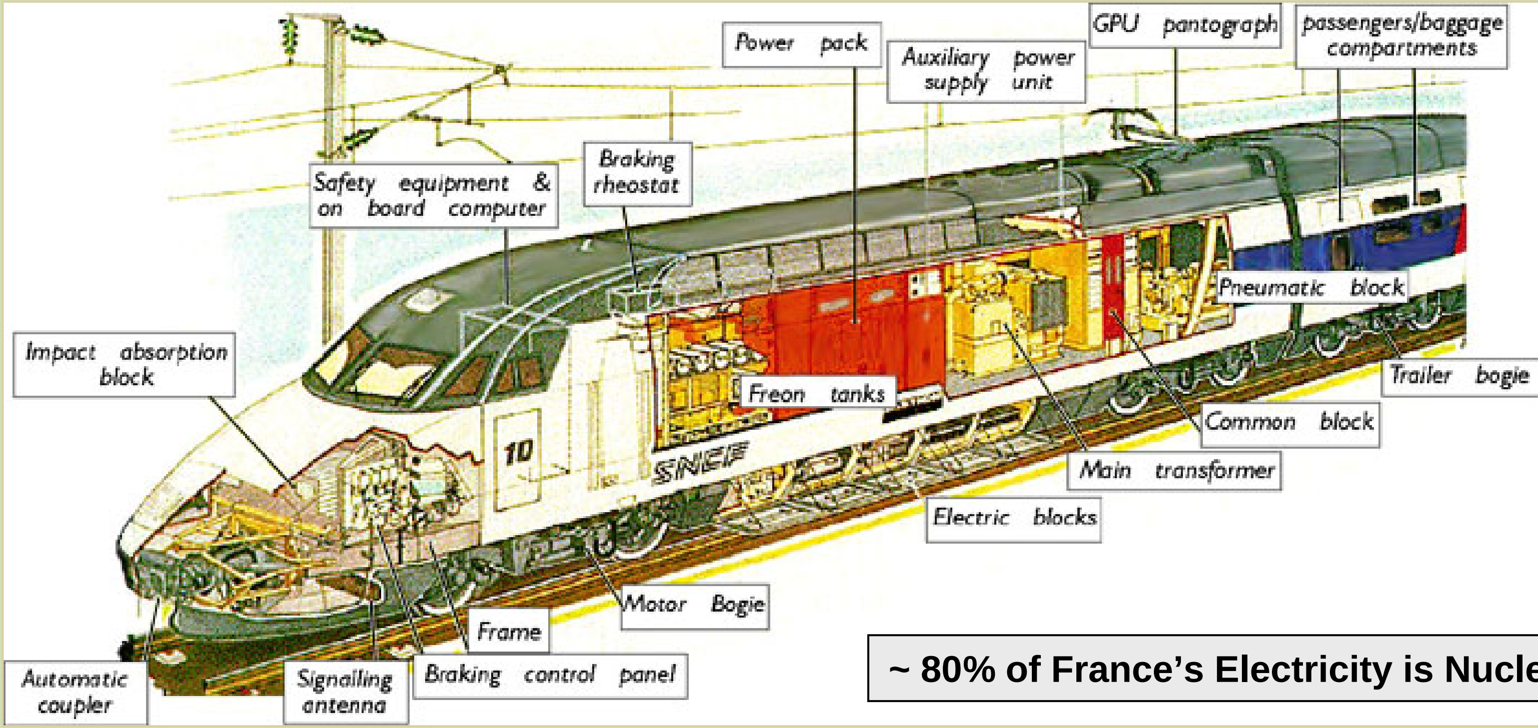
Above, plus
Fuel Cells?

1 Degree of Freedom (always on track)
+
Steel On Steel (Low C_{rr}, Weight Tolerant)
=
Wide Fuel Flexibility

Our most omnivorous mode of transportation

Fast Passenger Rail
(French TGV, Japanese Bullet Train)

- First TGV powered by Gas Turbine (ca. 1972)
- Changed to Electrical Power in Response to Arab Oil Embargo, 1974
- In Regular Service since 1981

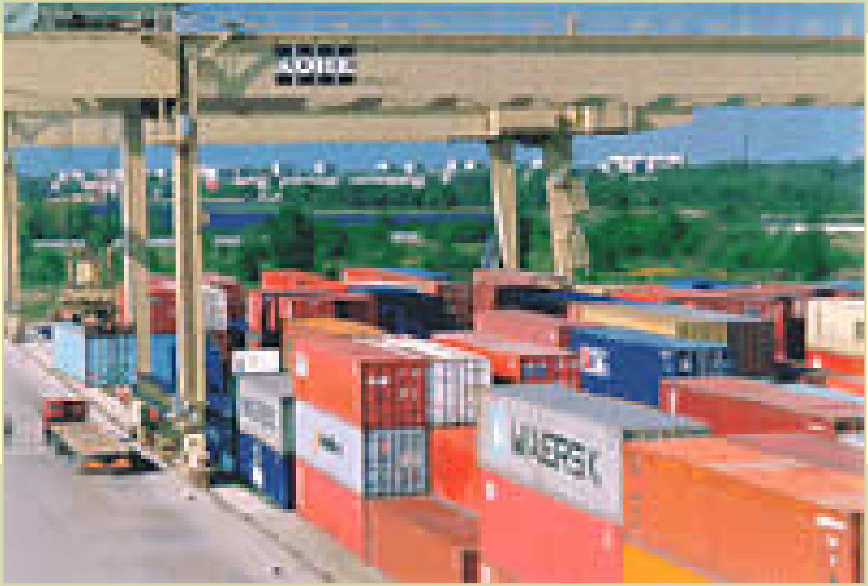


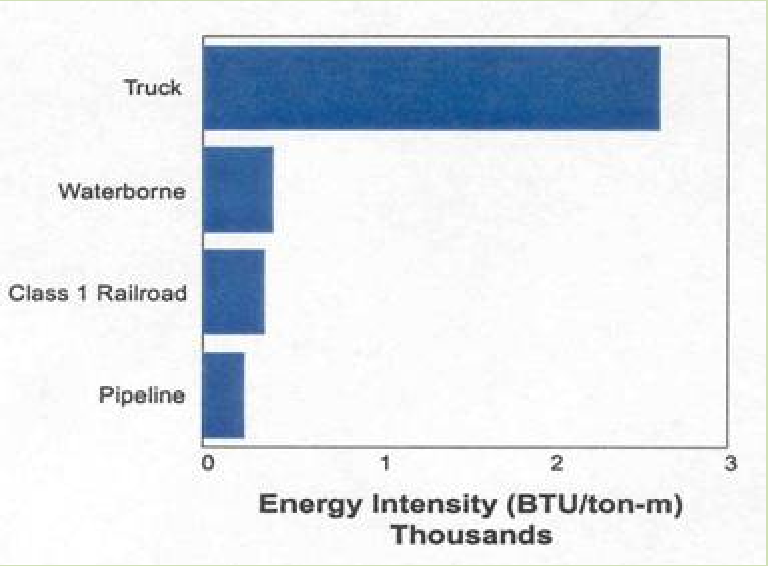
~ 80% of France’s Electricity is Nuclear

Container Freight

Multi-Mode

- Ship
- Train
- Truck





Comparing Transportation Modes

Current Fuel:
- Gasoline (SI)
- Diesel (CI)

Future Fuel:
- Liquids
- Fuel Cell?
- Battery?

2 Degrees of Freedom

Moderate Weight Sensitivity

Comparing Transportation Modes

Three Degrees of Freedom
Very High Weight Sensitivity
Very Demanding Fuel Requirements

Current Fuel:

- AvGas (SI)
- Jet A, JP-4 (Turbines)

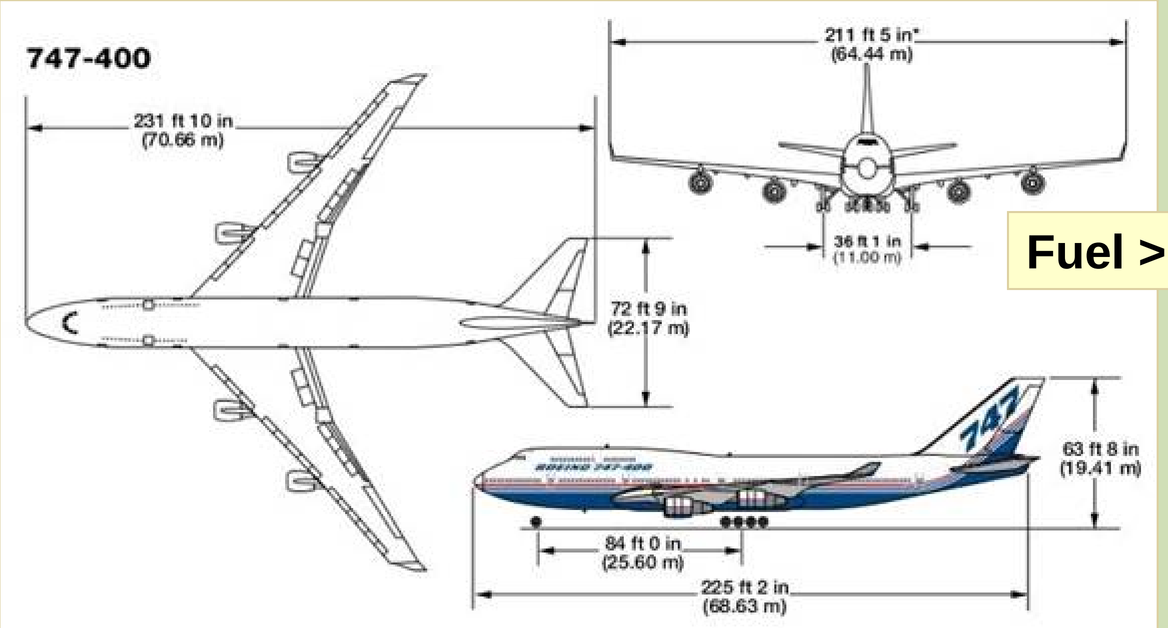
Future Fuel:

- Liquids
- (Incl. Biodiesel)
- Alternatives (Fuel Cell, etc) are tenuous!

Aircraft Weight Sensitivity

Example: Boeing 747- 400 from Tokyo—New York

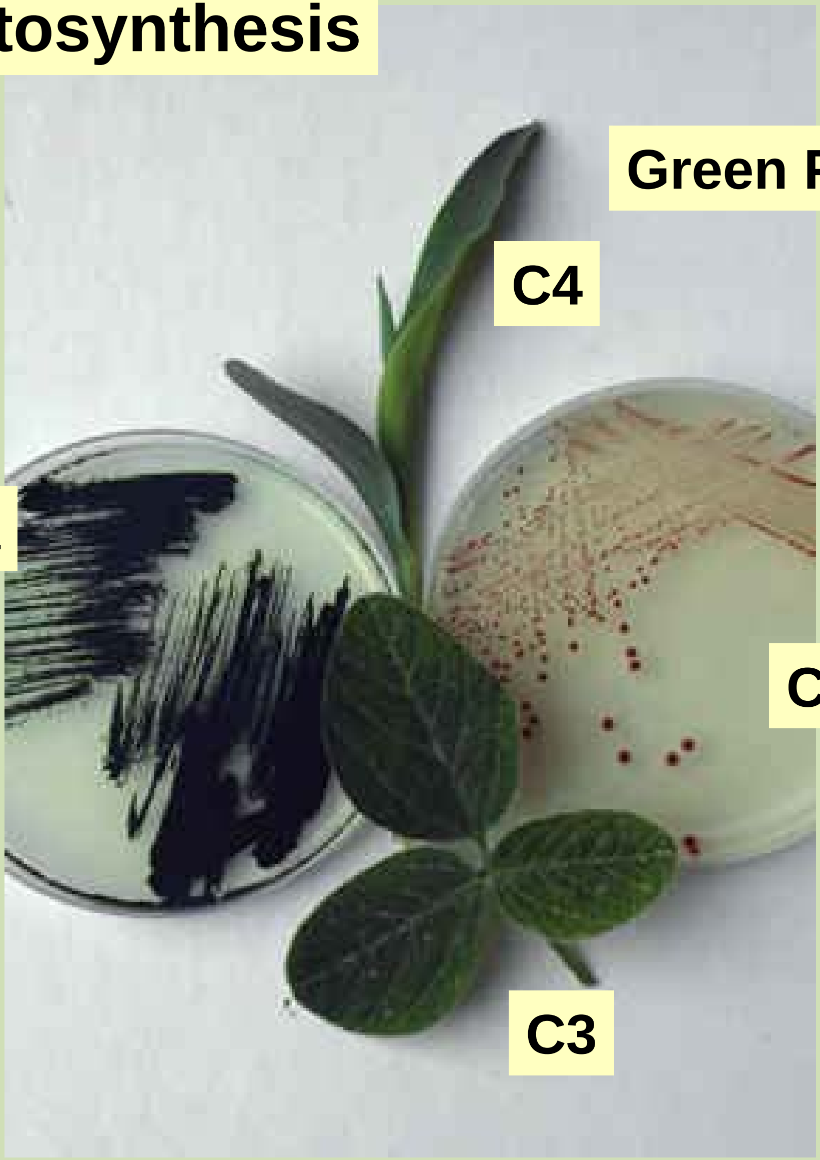
Take-Off Weight	=	375 Tons
Landing Weight	=	250 Tons
Fuel Burn	=	125 Tons
Fuel Reserve	=	25 Tons



Fuel > 1/3 of Take-Off Weight

Source: Boeing

Forms of Photosynthesis



Efficiency of Photosynthesis

Sunlight to Sugar

11% is Absolute Top Theoretical Efficiency

Losses are Estimated at:

Evolutionary Survival	**20-25%**
Respiration (Structure, etc)	**20-100%**

So New Practical Peak = ~5%

Source: Smil

Efficiency of Photosynthesis

Crassulacean Acid Metabolism

Separates (in time) energy absorption And carbon fixation

Most Common Limit to Photosynthesis is <u>WATER</u>

Lowest Transpiration Loss:

400-500 moles H_2O per mole CO_2 Fixed

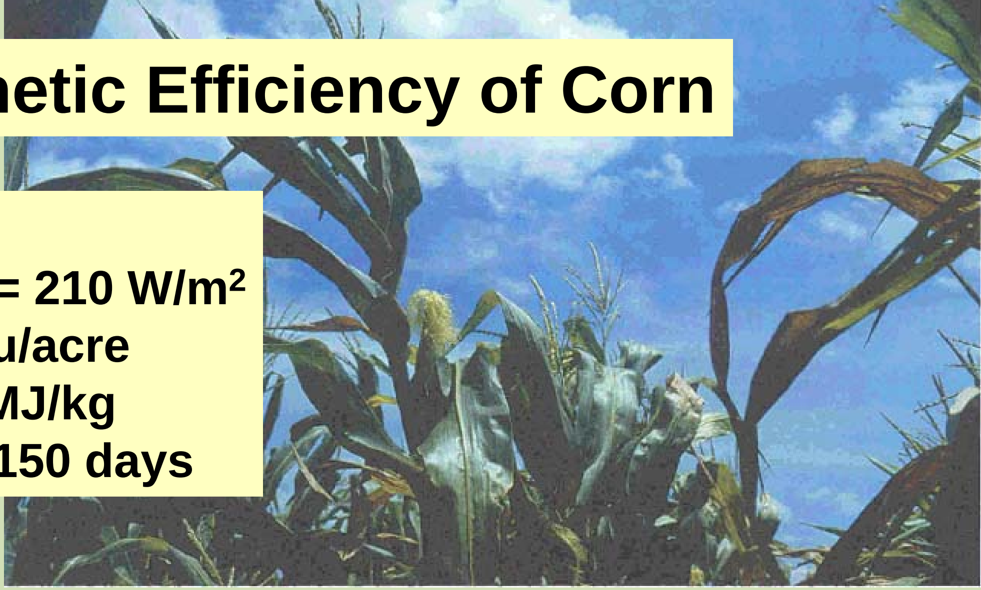
Source: Smil

Comparing Photosynthetic Pathways

	C3	C4
Saturation of Radiation, W/m^2	300	None
Best Temperature, ^oC	15-25	30-45
Moles H_2O per mole CO_2 Fixed:	900-1200	400-500
Maximum Daily Growth: g/m^2	34-39	50-54
Daily Max, Average for Season: g/m^2	13	22

Source: Smil

Example: Photosynthetic Efficiency of Corn



Given:

Average Radiation = 210 W/m^2
Grain Yield = 200 bu/acre
Grain Energy = 17 MJ/kg
Growing Season = 150 days

Total Season Radiation:

$$210\ W/m^2 * 3600 * 24 * 150 = 2.72 * 10^9\ J/\ m^2$$

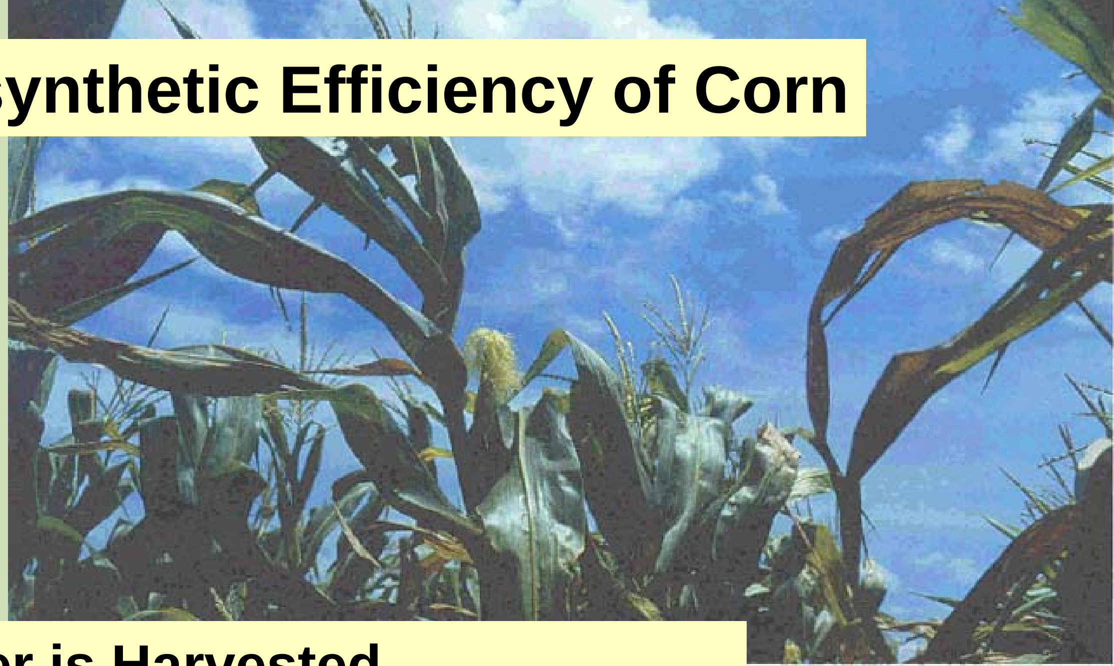
Grain Energy:

$$200 * 56 * 17 * 2.47/2.2 = 2.1 * 10^5\ MJ/ha$$

Photosynthetic Efficiency (Grain Only):

$$2.1 * 10^5\ MJ/ha\ /\ 2.72 * 10^9\ J/\ m^2 = \underline{0.77\%}$$

Example: Photosynthetic Efficiency of Corn



If Stover is Harvested,
and MOG/Grain = 1:

Photosynthetic Eff Would ~Double

To ~ 1.5%

Solar Conversion Efficiency

C3 Crops	0.1-0.7%
Best C4 (Sugar Cane)	1.5-2.5%
Global Mean	~0.3%

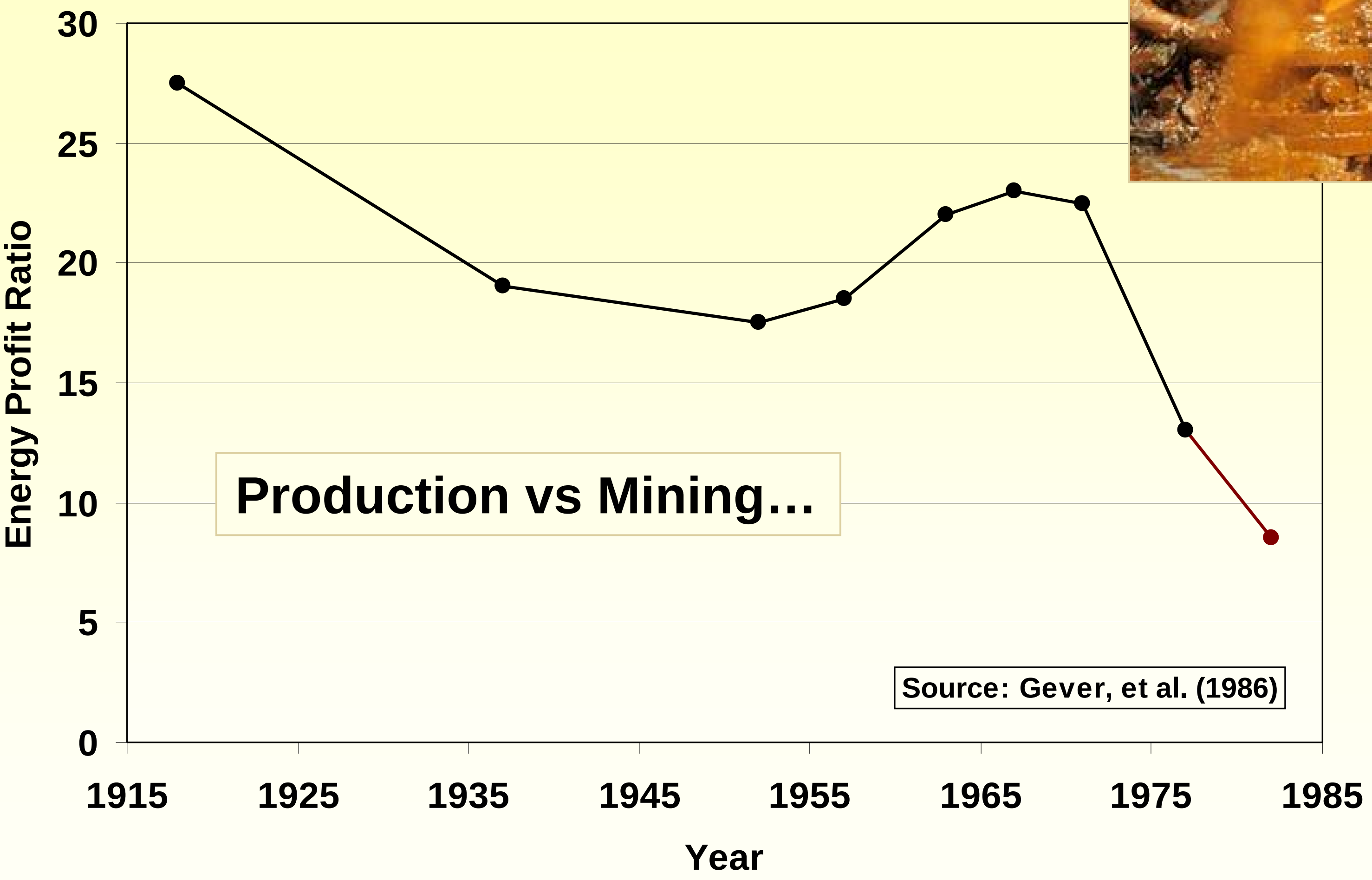
Kansas Farmland (0.5%)	$500-4000/ac
PV Array (12%)	$2,000,000/ac

Source: Smil

BioEnergy Issues:
Does it Really Produce Energy?

Energy Profit Ratio = Energy Out / Energy In

Energy Profit Ratio
US Domestic Petroleum



Agricultural Energy Inputs:

Production

Direct

- Field Operations
- Irrigation
- Grain Drying
- Management

Embodied

- Fertilizer
- Seed
- Chemicals
- Machinery

Energy Outputs:

Fuel

- ETOH
- BioDiesel
- Others

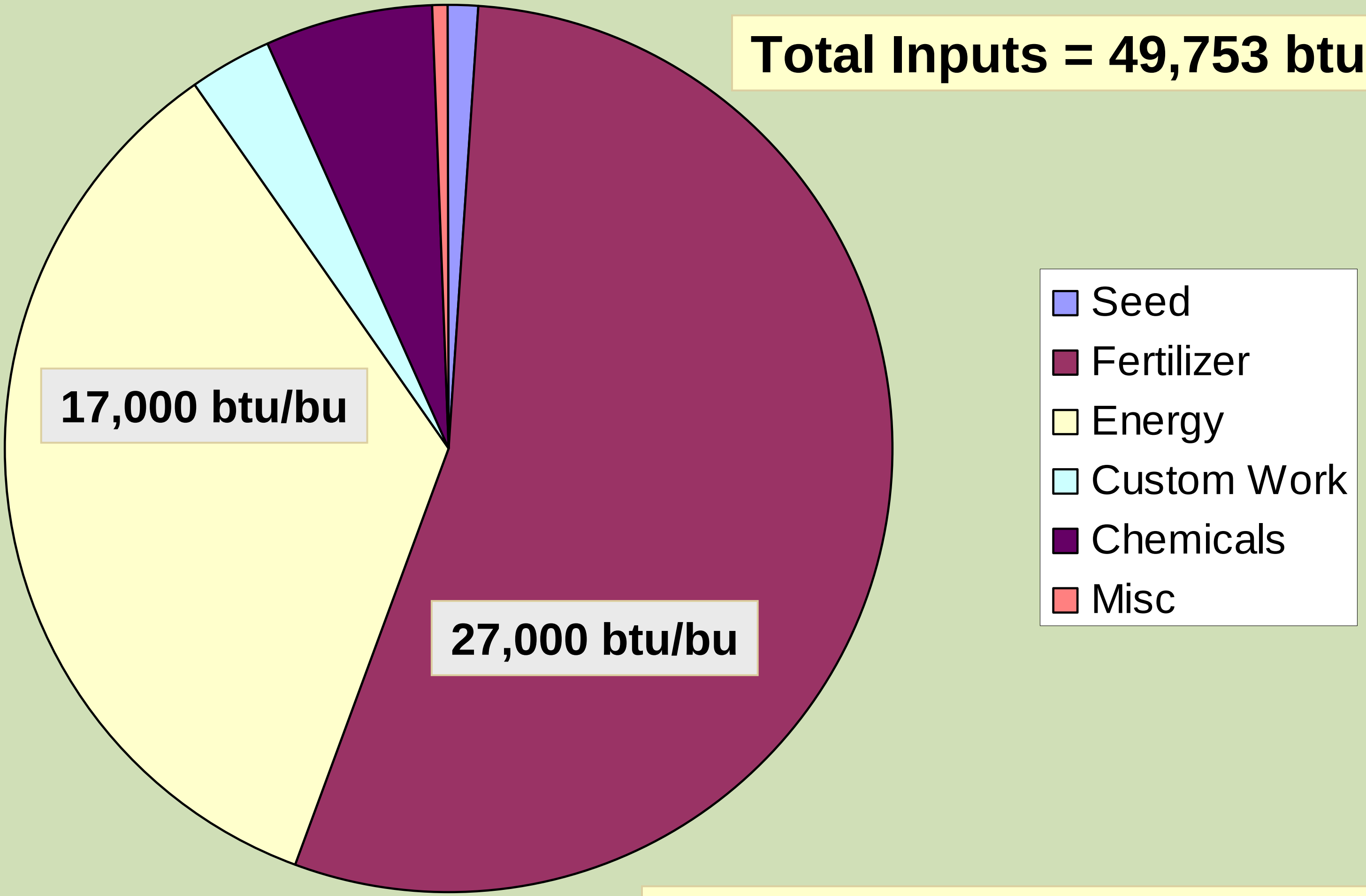
CoProduct

- DDGS
- Gluten Feed
- Seed Meal
- Pesticides
- Others

The CoProduct may have more value (both $ and BTU) than the fuel.

Energy Inputs for Corn Production:

Total Inputs = 49,753 btu / bu



Source: Shapouri, Duffield, & Wang, 2004

Energy Balance for Ethanol Production:

	No Credits BTU/Gal.	W/Credits BTU/Gal.	W/Credits Adjusted BTU/Gal.
Corn Production	18713	12350	18713
Corn Transport	2120	1399	2120
Ethanol Conversion	49733	30586	49733
Ethanol Distribution	1487	1467	1487
Total Energy Used	72052	45802	72052
Net Energy	4278	30528	30528
Ethanol Energy Value	76330	76330	102580
Energy Out/In	1.06	1.67	1.42

Source: Shapouri, Duffield, & Wang, 2004

Opportunities for Improving Ethanol's Energy Balance:

Corn Fertilization, especially Nitrogen

Ethanol Processing (Cogen)

Biodiesel Energy Profit Ratio:

Biodiesel Feedstocks: wide variety of plant oil and animal fats.

The most comprehensive analysis (Sheehan, et al, 1998) considered Soybean oil (>300 page report).

Conclusion: Soy Biodiesel EPR = 3.21.

Other feedstocks (esp. non-legumes) will have lower/higher EPR.

Fossil Inputs to Soy Biodiesel:

	MJ Fossil/MJ Biodiesel
Soybean Agriculture	0.0656
Soybean Transport	0.0034
Soybean Crushing	0.0796
Soy Oil Transport	0.0072
Soy Oil Esterif. (incl. MEOH)	0.1508
Biodiesel Transport	0.0044
Total	0.3110

Source: Sheehan, et al., 1998

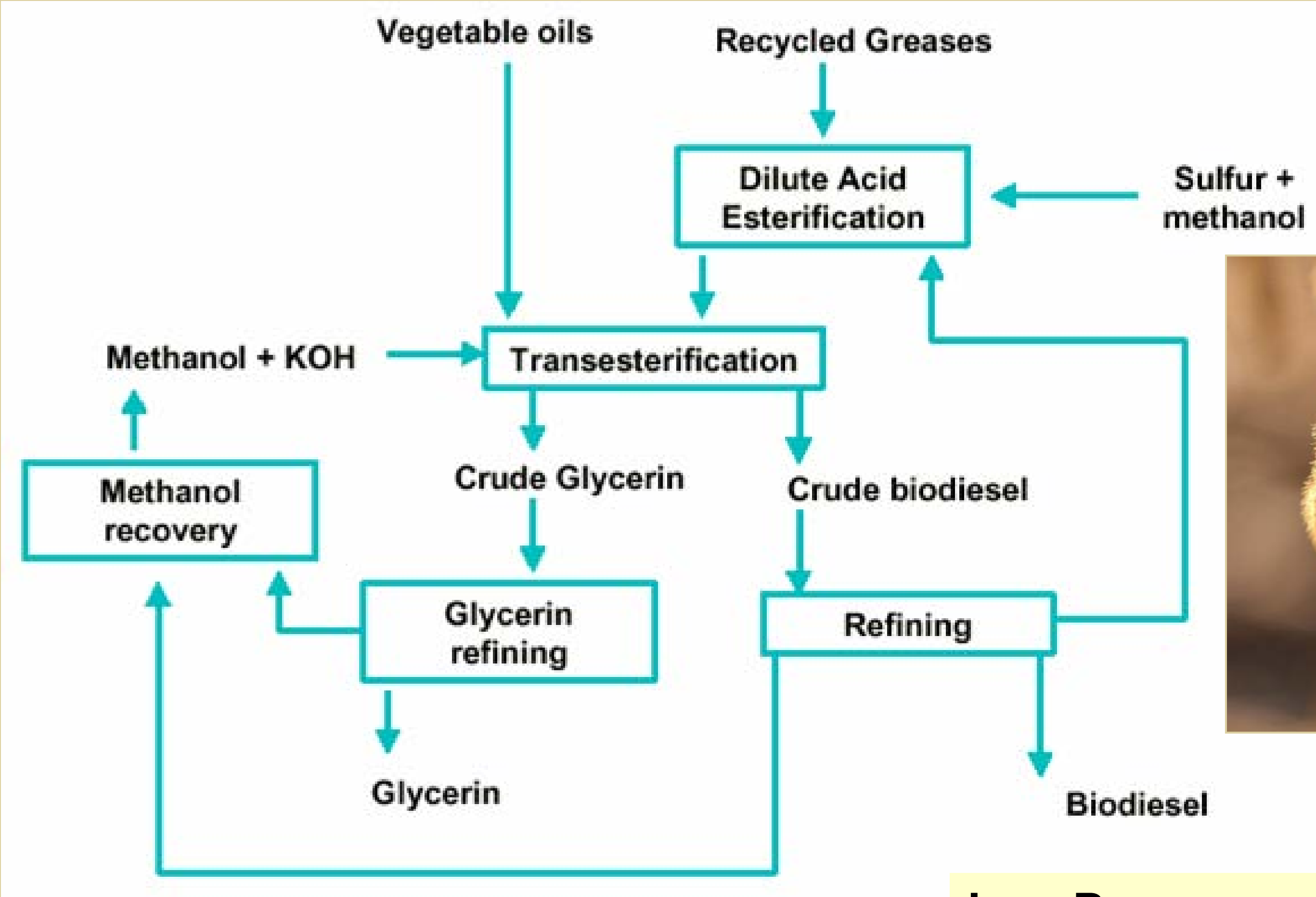
Other Biodiesel EPRs:

	Energy Out/Energy In
Corn Oil, Illinois	3.95
Cotton Seed Oil, Texas	1.76
Crambe, Kentucky	3.11
Peanut, Georgia	2.26
Spring Rape, Canada	4.18
Safflower, California	3.39
Soybeans, Illinois	4.56
Sunflowers, North Dakota	3.5

All Crops Dryland Production

Source: Goering & Daugherty, 1982

Basic Esterification:



Low Pressures
Low Temperatures

Esterification Reduces Viscosity

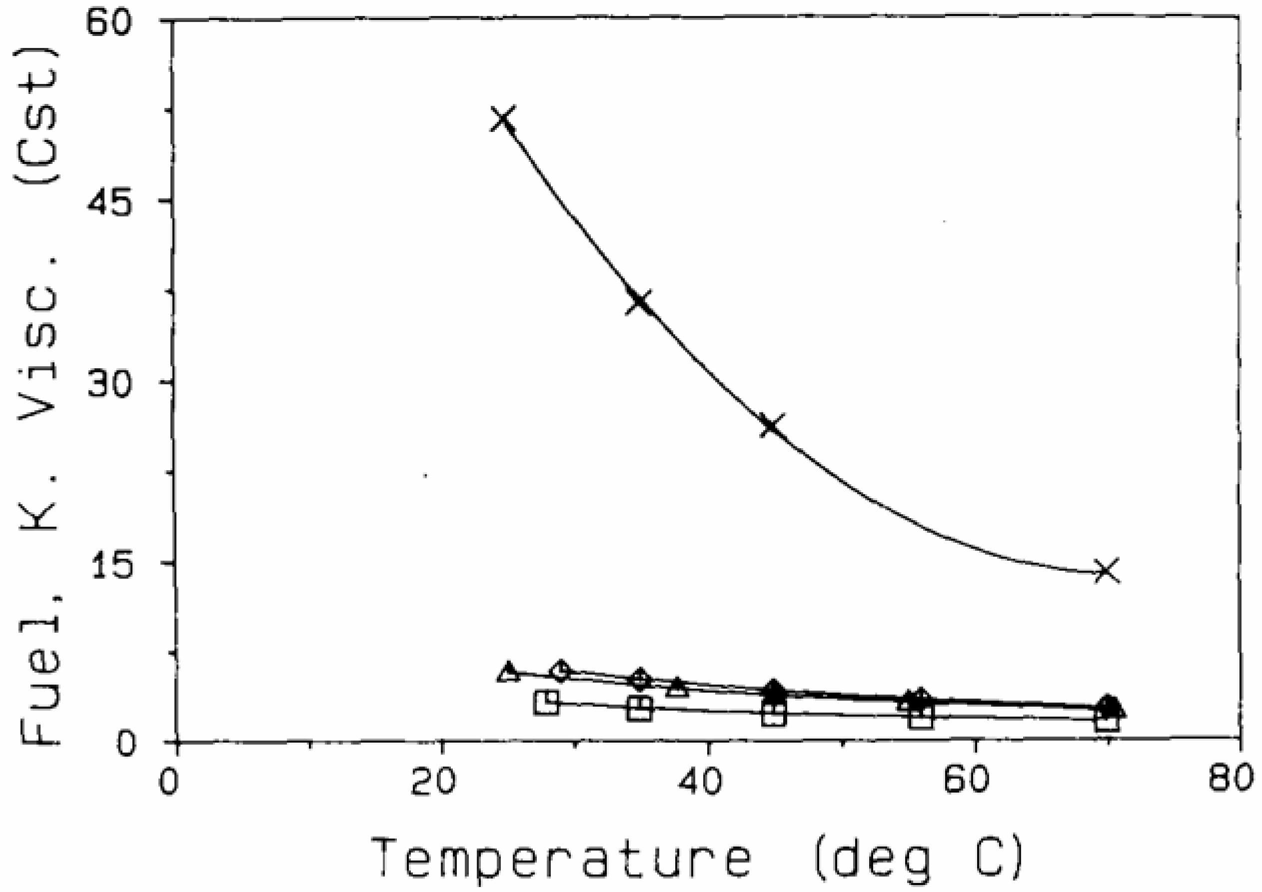


FIG. 1. Viscosity of soybean oil, soybean oil esters and diesel fuel in centistokes as a function of temperature, C. ⊞—⊞ Diesel, ◇—◇ ethyl, △—△ methyl, ×—× soybean oil.

Source: Clark, et al., 1984 (KSU)

Biodiesel Properties:

	Unit	Diesel	MESO
Specific Gravity	kg/L	0.82-.85	0.86-.90
Viscosity	Cst	2-3	3.5-5
Lower Heating Value	MJ/kg	42-43	40
Cetane Number		45-49	48
Flash Point	C	74	>100

Source: Clark, et al., 1984 (KSU)

Power From Soy Esters

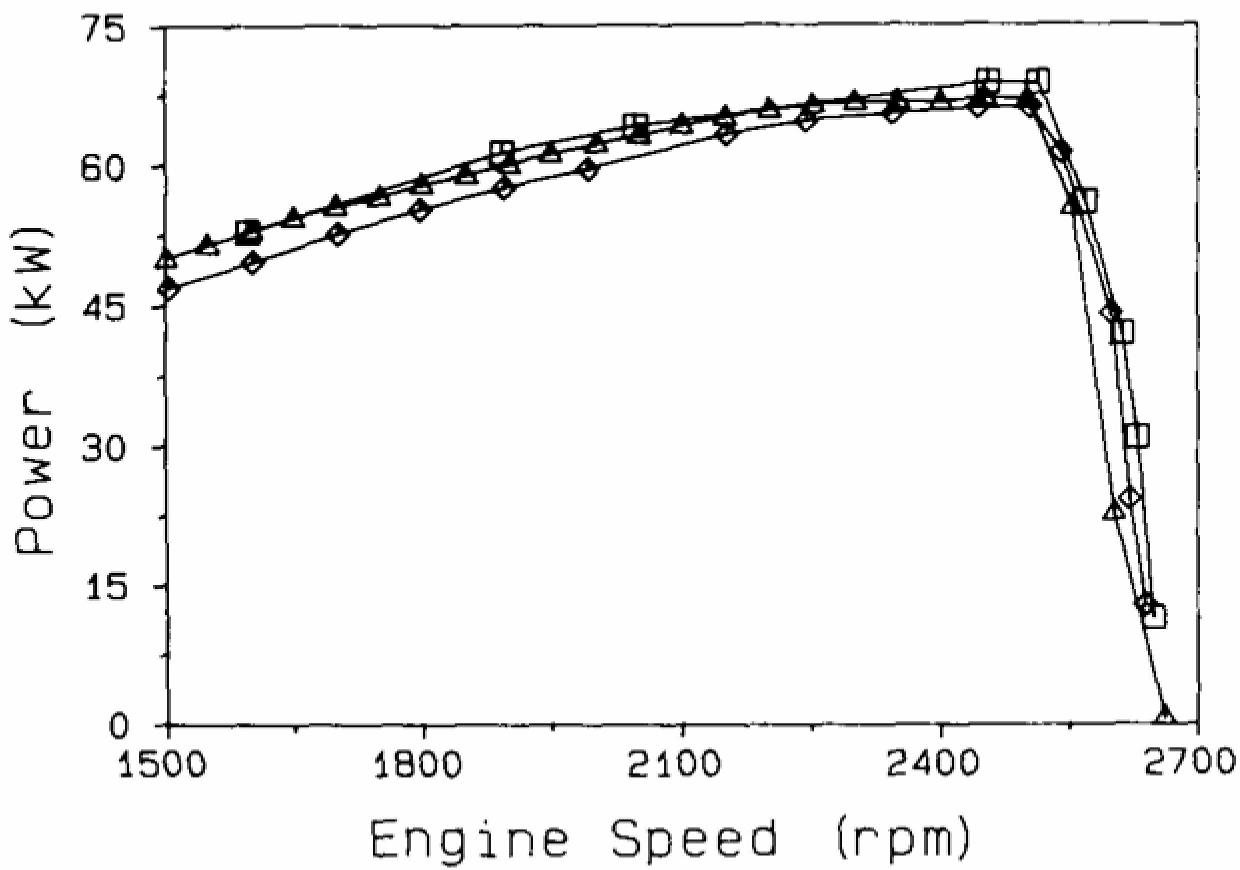


FIG. 3. Power, kW, vs speed for John Deere 4239TF engine at full rack for soybean oil esters and diesel fuel. □—□ Diesel, ◇—◇ ethyl, △—△ methyl.

Source: Clark, et al., 1984 (KSU)

Desirable Traits for Energy Crops

Legume (or low protein product)

Perennial (low energy inputs)

Low Processing Energy

Good Yields on Dryland

Two Paths:

Adapt food crops to energy production

Domesticate new energy crops

Soybean
Glycine max

Temperate

Legume

Annual

Cultivated for 3000 yrs

Seed Yield	3.1 Mg/ha
Oil Content	17-26%
Oil Yield	650 kg/ha

Ref: CIGR V.

Seed Yield	2 Mg/ha (30 bu/ac)
Oil Content	18%
Oil Yield	360 kg/ha (46 gal/ac)

Sunflower
Helianthus annus

Temperate

Annual

Seed Yield	3.7 Mg/ha
Oil Content	35-40%
Oil Yield	1400 kg/ha

Ref: CIGR V.

Seed Yield	1.7(dry)-3.4 (irr) Mg/ha
Oil Content	40%
Oil Yield	700-1400 kg/ha (90-180 gal/ac)

Ref: KSU Hybrid Trials

Peanut
Arachis hypogaea

Temperate

Annual

Legume

Seed Yield	5 Mg/ha
Oil Content	36-50%
Oil Yield	2000 kg/ha

Ref: CIGR V.

Seed Yield	2.5 Mg/ha (irr)
Oil Content	48%
Oil Yield	1200 kg/ha (150 gal/ac)

Ref: KSU (ASAE MCR85-142)

Castor
Ricinus communis

Temperate

Perennial Grown as Annual

Ricin (potent toxin)

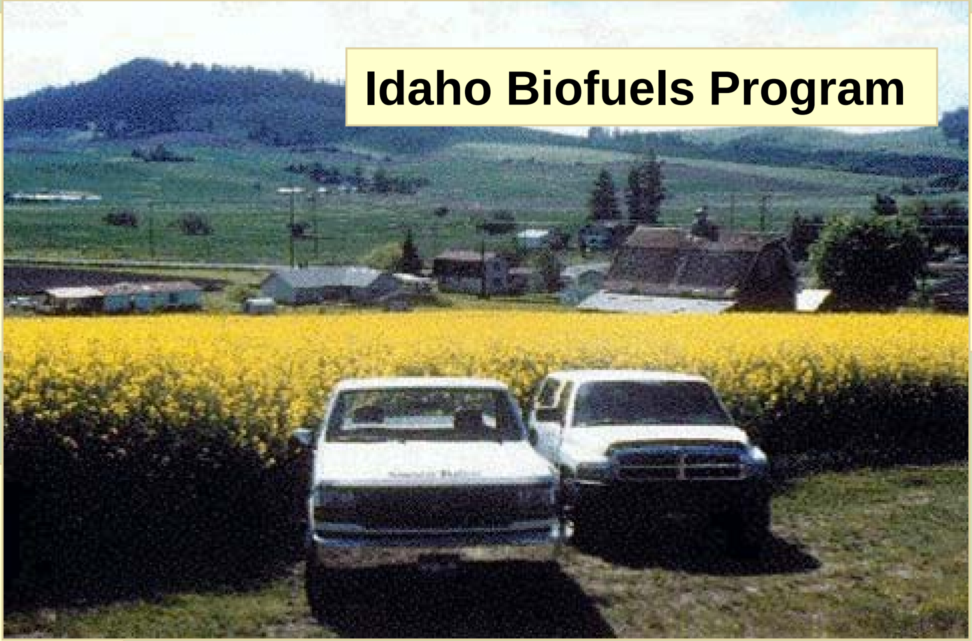
Seed Yield	5 Mg/ha
Oil Content	35-55%
Oil Yield	2250 kg/ha
	(285 gal/ac)

Ref: CIGR V.

Lubricant "Castrol"

Grown in SW KS & TX panhandle, WWII era.

Rape
Canola
(low erucic Rape)
Brassica napus



Temperate

Annual

Pacific NW, Canada, China

Seed Yield	3 Mg/ha
Oil Content	33-40%
Oil Yield	1100 kg/ha (140 gal/ac)

Ref: CIGR V.

Safflower
Carthamus tinctorius

Temperate

Annual

Pacific NW

Seed Yield	4.5 Mg/ha
Oil Content	25-37%
Oil Yield	1300 kg/ha

Ref: CIGR V.

Crambe
Crambe abyssinica

Temperate
Annual

German-French Tests (dry):

Varieties	1996	CEB 9402-CR		CEB 9404-CR		CPRO-9103-16
Site		A	E	A	E	A
Yield *	dt/ha (91% dm)	19,84	19,03	10,11	14,82	23,20
Oil content	% (ADM)	37,9	37,7	37,6	38,3	35,1
Oil yield	dt/ha (91% dm)	7,52	7,17	3,80	5,68	8,14
Erucic acid %		59,9	58,8	59,9	57,9	61,3

"dt" = 100 kg

Seed Yield	**5 Mg/ha**
Oil Content	**36%**
Oil Yield	**1800 kg/ha (225 gal/ac)**

Ref: CIGR V.

Plant-Derived Liquid Fuels
Four Options

Table 1. Liquid biofuels by feedstock and land class.

	Arable Land	Nonarable Land
Starch and Cellulose-Based	Ethanol from Grain Ethanol from Crop Residues	Cellulosic Ethanol from Perennials (herbaceous and woody)
Lipid-Based	Biodiesel from Annual Oilseeds	***Biodiesel from Perennial Oilseeds***

Expanding Land Available for Energy: Perennial vs. Annual Agriculture

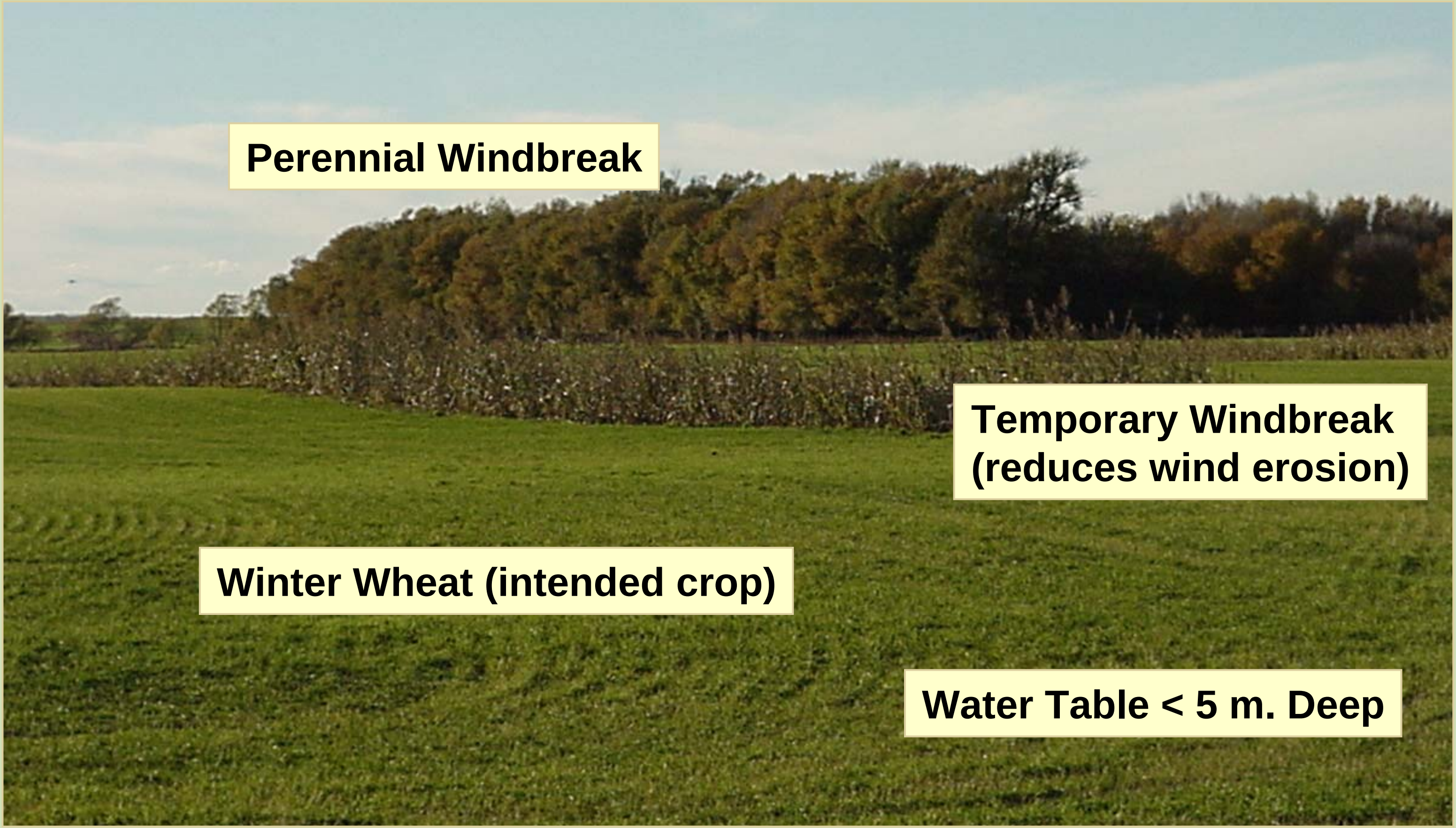
Factors that Render Land Non-Arable:

- Steep Slopes
- Shallow Topsoil
- Sandy Topsoil
- Surplus or Deficient Water
- Variable Climate
- Rocks

Perennial Agriculture SHOULD BE far less vulnerable.

Class IV Land: Marginally Arable

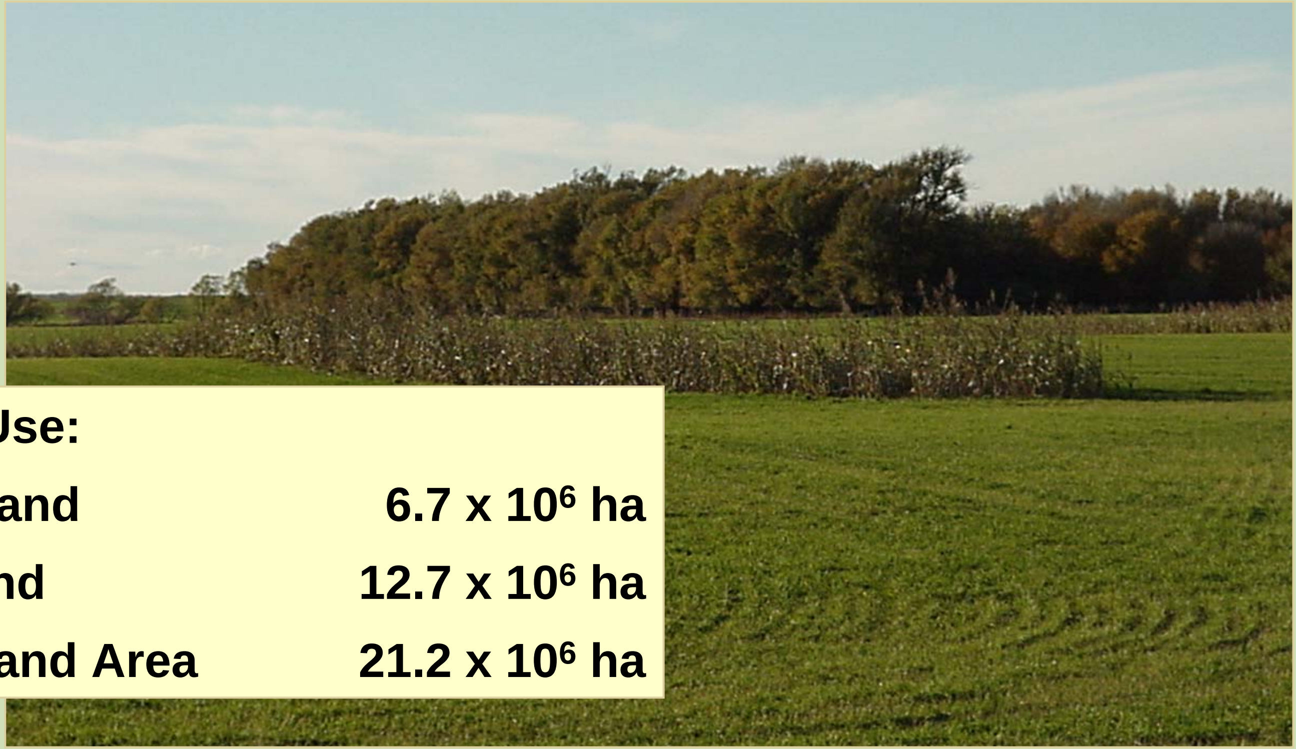
Sandy Topsoil (High Erosion & Low Water Capacity)



Why Force Marginal Land Into Annual Agriculture?

Kansas Cash Rental Rates:

Rangeland	\$31.12/ha
Non-Irrigated Cropland	\$88.92/ha



Kansas Land Use:

Rangeland	6.7×10^6 ha
Cropland	12.7×10^6 ha
Total Land Area	21.2×10^6 ha

Is $15/ac the Best We Can Do?

Biodiesel From Perennial Oilseeds

Potential Benefits:

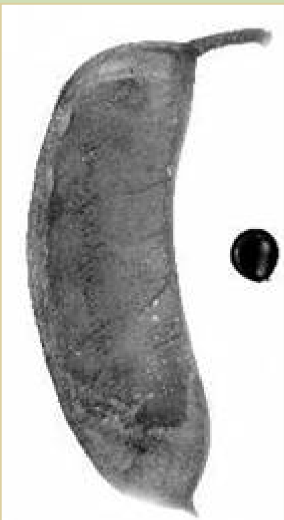
- **Utilize Marginal Land**
- **High Energy Profit Ratio**
- **Low Processing Energy**

Kentucky Coffee Tree
Gymnocladus dioica

Large (20 m. tall) Legume

Cotyledon: 32% protein, 23% fat

Oil Yield ~ 200 l/ha



Chinese Tallow Tree
Sapium sebiferum

Tropical

Perennial

Invasive Weed in Florida, Texas

Seed Yield	14 Mg/ha
Oil Content	55%
Oil Yield	7700 kg/ha
	(970 gal/ac)

Ref: CIGR V.

Jatropha curcas

Tropical Shrub ~ 3 m tall
E. Africa

Seed Yield	8 Mg/ha
Oil Content	50%
Oil Yield	4000 kg/ha (500 gal/ac)

Ref: CIGR V.

African Oil Palm
Elaeis Guineensis

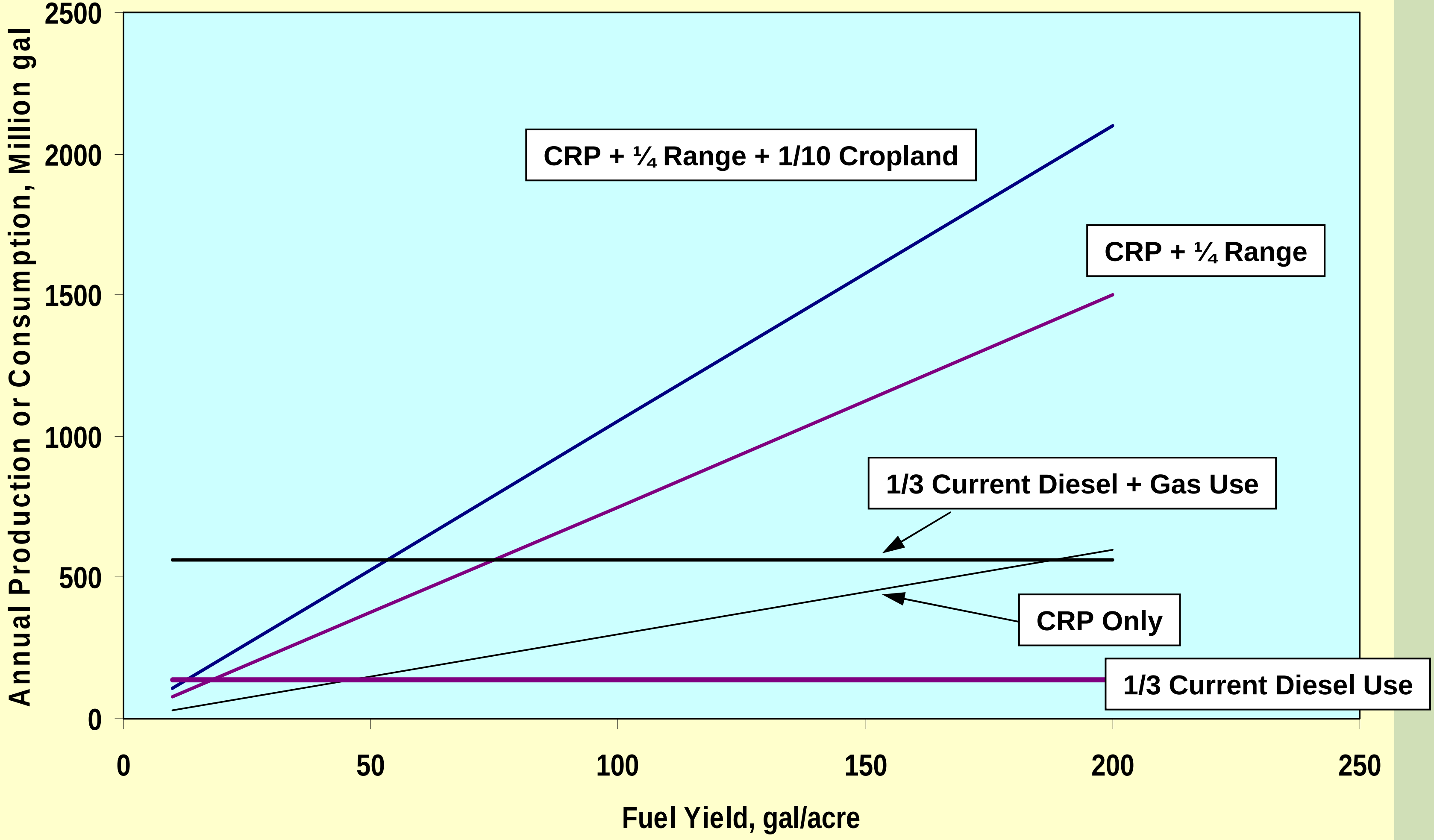
West Tropical Africa

Oil Yield 2200 kg/ha

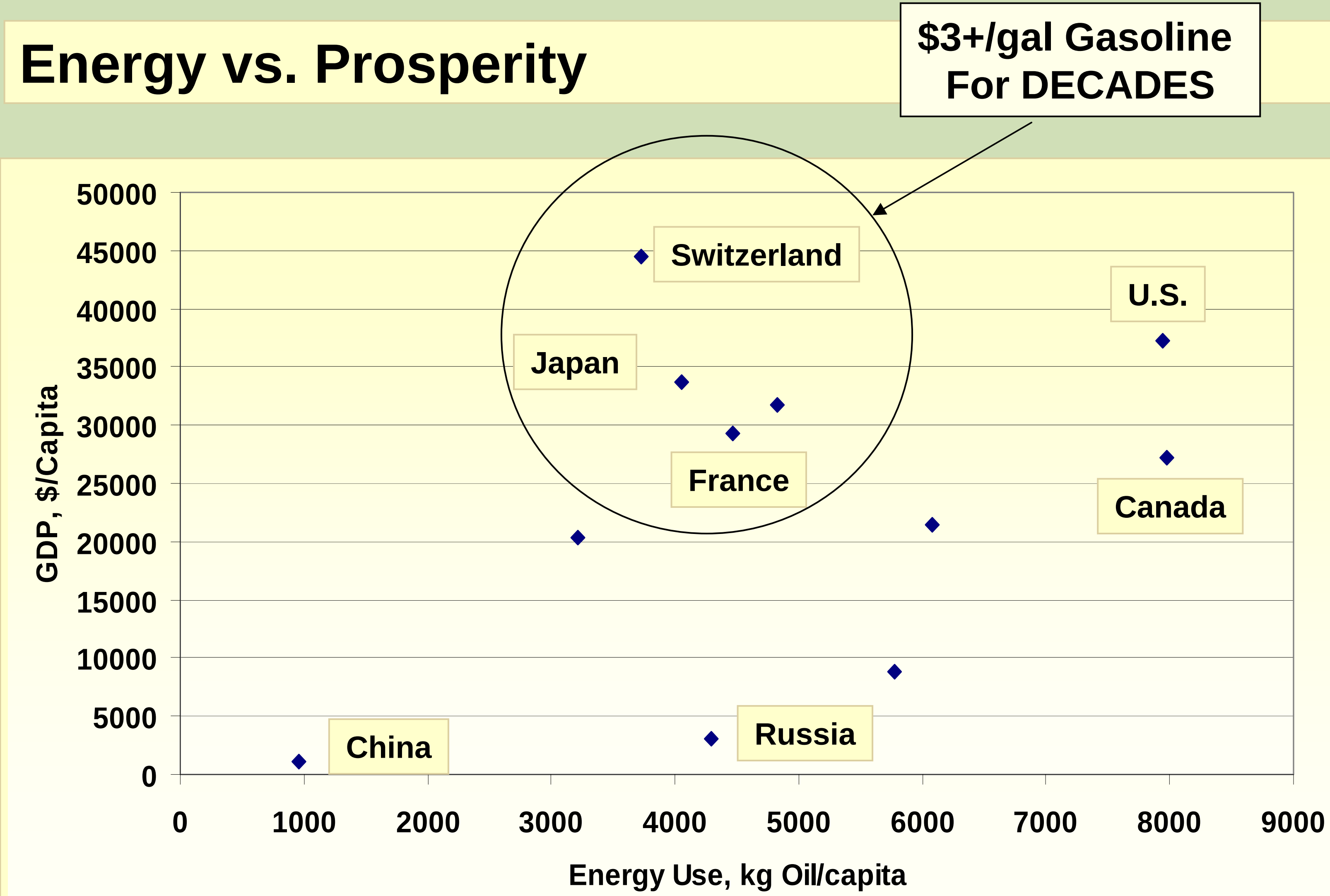
(280 gal/ac)

Ref: CIGR V.

Kansas Transportation Energy vs Land Resource



Energy vs. Prosperity



Source: Economist World in Figures, 2006

“The Americans will always do the right thing... after they’ve exhausted all the alternatives.”

Sir Winston Churchill