2.61 Internal Combustion Engines
Spring 2008

# Bio-fuels and hybrids

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# The backdrop

# Transportation and Mobility

- Transportation/mobility is a vital to modern economy
  - Transport of People
  - Transport of goods and produce
- People get accustomed to the ability to travel

## Transportation needs special kind of energy source

- Vehicles need to carry source of energy on board
- Hydrocarbons are unparalleled in terms of energy density
  - For example, look at refueling of gasoline
    - ~40 Liters in 2 minutes (~0.25 Kg/sec)
  - Corresponding energy flow

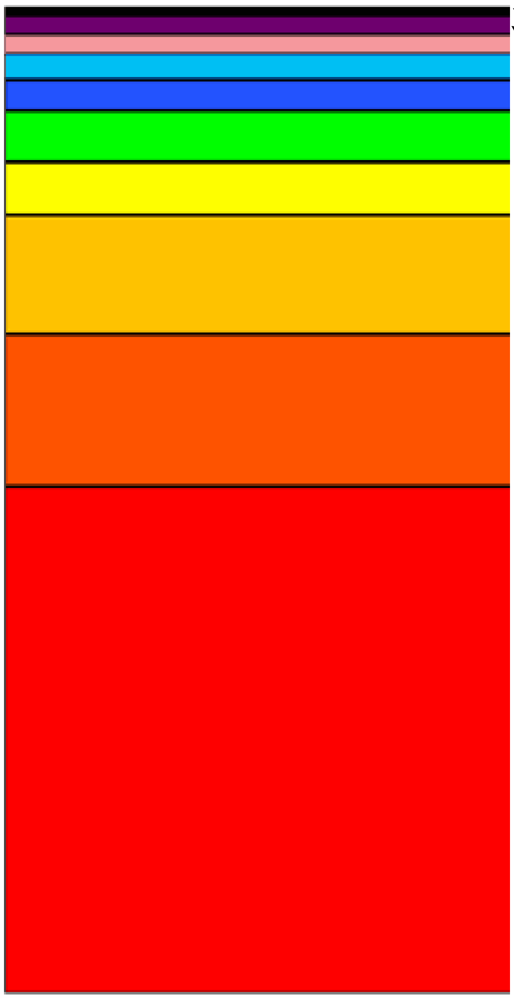
    = 0.25 Kg/sec x 44 MJ/Kg

    = 11 Mega Watts

**Liquid hydrocarbons !**

# What is in a barrel of oil ?

(42 gallon oil → ~46 gallon products)

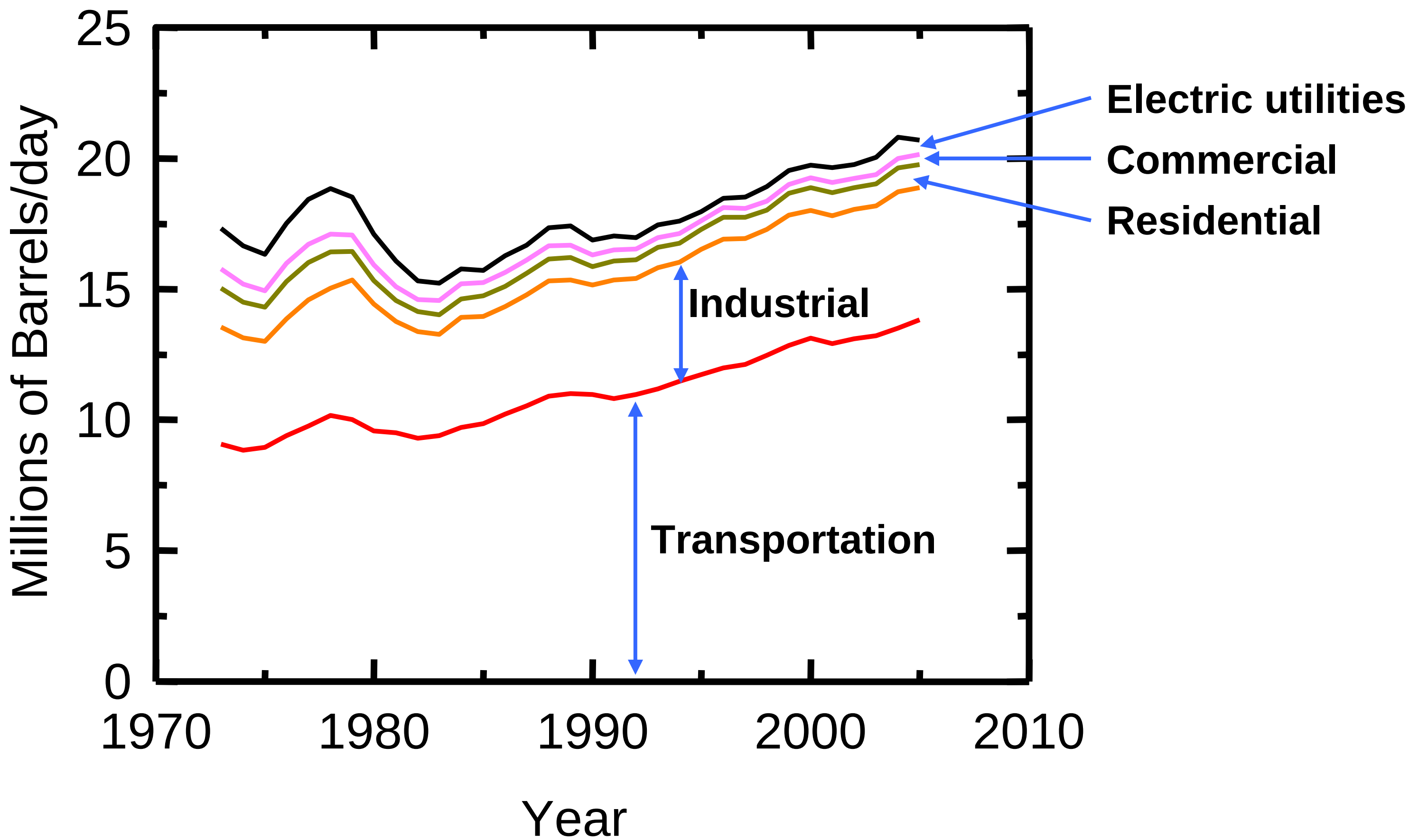


## Typical US output

| | |
|---|---|
| Lubricants | 0.90% |
| Other Refined Products | 1.50% |
| Asphalt and Road Oil | 1.90% |
| Liquefied Refinery Gas | 2.80% |
| Residual Fuel Oil | 3.30% |
| Marketable Coke | 5.00% |
| Still Gas | 5.40% |
| Jet Fuel | 12.60% |
| Distillate Fuel Oil | 15.30% |
| Finished Motor Gasoline | 51.40% |

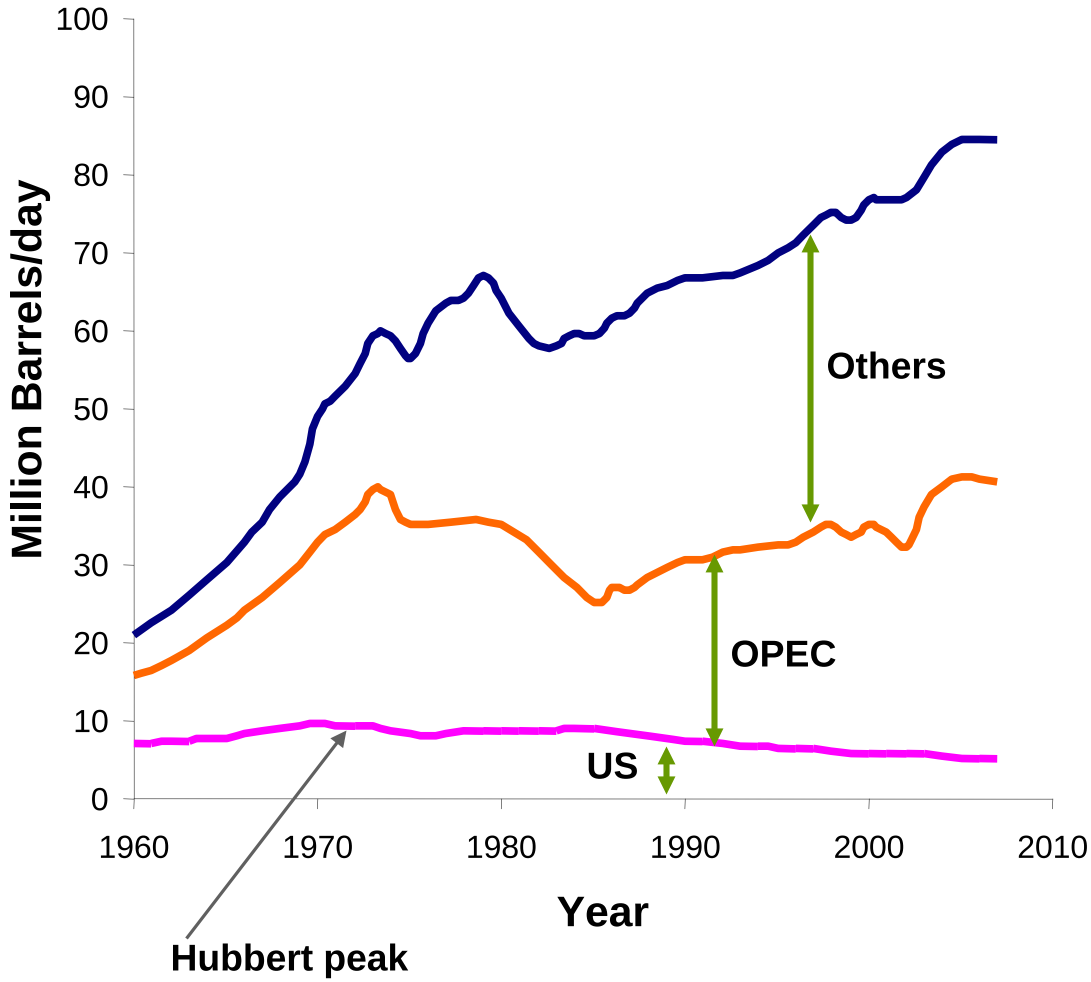
**Source: California Energy Commission, Fuels Office**

# US Use of Petroleum by sector




Source: US Dept. of Energy

# Oil Supply (annual average up to 2007)




Source: EIA

# The world Hubbert peak

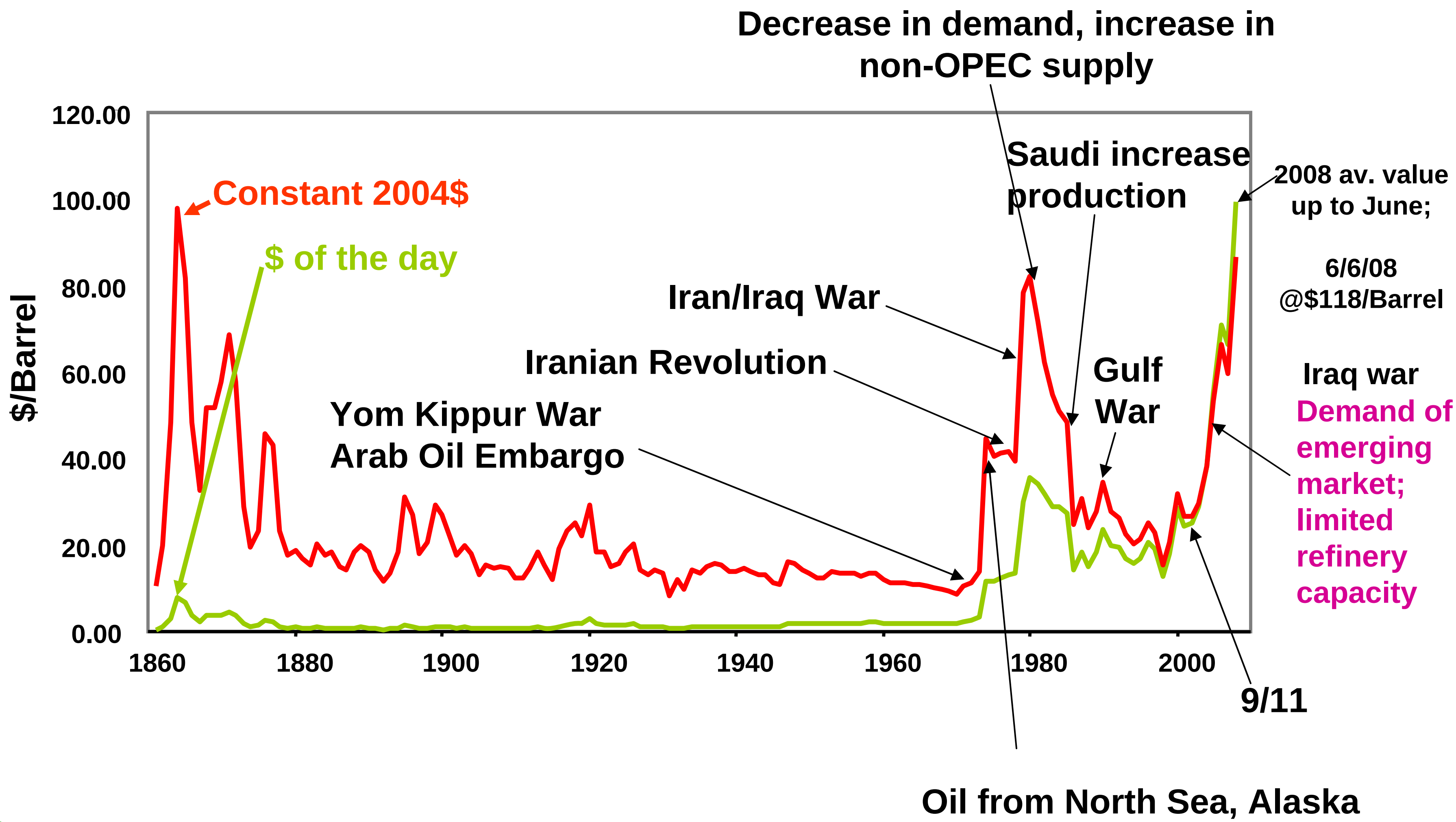
(excluding OPEC & Russian production)

**2003**

Image removed due to copyright restrictions. Please see Fig. 9 in Zittel, Werner, and Jörg Schindler. "Future World Oil Supply." Salzburg, Germany: International Summer School on the Politics and Economics of Renewable Energy, July 2002.

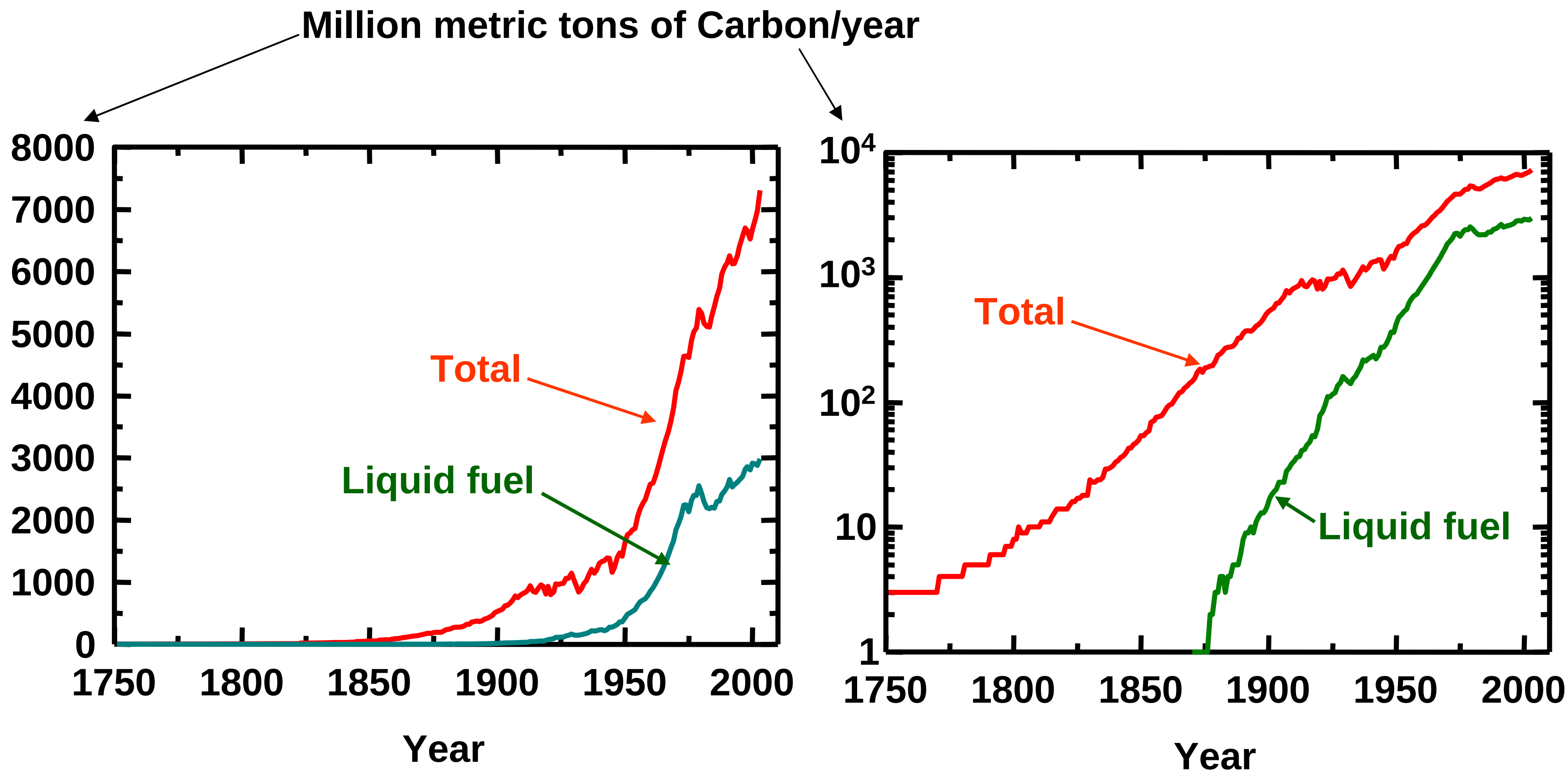
**Source: http://www.fossil.energy.gov/programs/reserves/npr/publications/npr_strategic_significancev1.pdf**

# Petroleum price




Sources:
Data from EIA; event labels from WTRG Economics

# $CO_2$ emissions from fossil fuel




Source: EIA

# The drive to bio-fuel

- Increasing demand of liquid fuel for transportation
  - Population
  - Society affluence
- Drive for lower $CO_2$ production
- Perceived decline of petroleum reserve
- Fuel price
- Government Policy
  - Tax credit
  - Required bio-fuel content

## What is bio-fuel?

# Dominant biofuels

**Usage**

Sugar based
(corn, sugarcane, …) → Ethanol

Cellulosic based
(switchgrass, wood, …) → Ethanol

Ethanol ⇒ E10, E20, E85, …

Compatible with current engine technology and fuel infra structure

Crop based
(rapeseed, soybean, …) → Bio-diesel

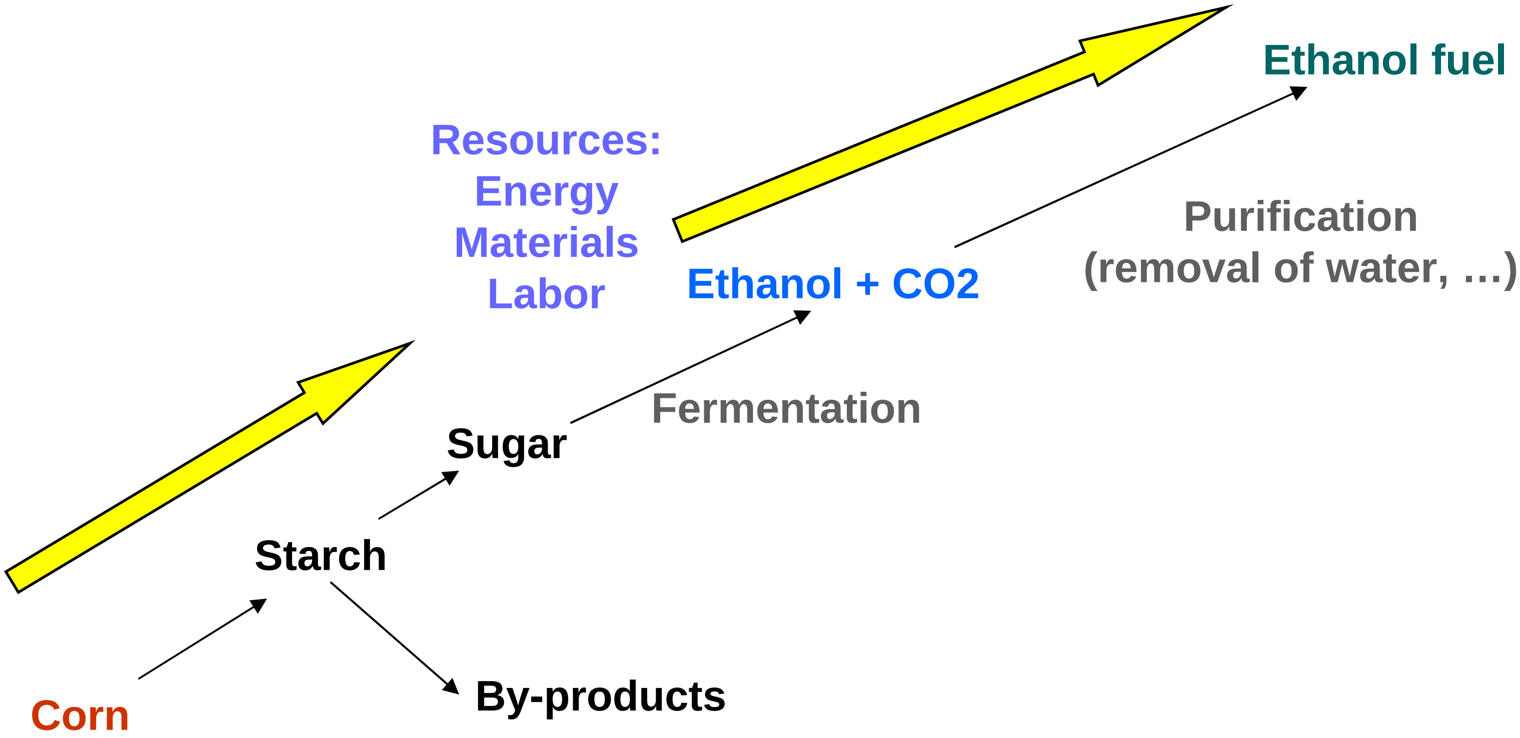
Wasted oil/ animal fat → Bio-diesel

Algae → Bio-diesel

Bio-diesel ⇒ B10, B20, ….

**(BTL fuel not included in this discussion)**

# Example: Ethanol production from corn



# Example: bio-diesel production

Bio-diesel (esters)

Purification
(removal of glycerol,
alkaline, fatty acid, …)

Resources:
Energy
Materials
Labor

Esters and glycerol

Transesterification using alcohol
(methanol) with alkaline catalyst

Oil (tri-glyceride)

Mechanical or solvent (hexane)
extraction + water removal

Soy,
rapeseed, …

| Tri-glyceride | | Alkaline Catalyst (KOH) | Esters | Glycerol |
|---|---|---|---|---|
| $CH_2\text{-OOC-}R_1$ | | | $R\text{-OOC-}R_1$ | |
| \| | | | | |
| $CH\text{-OOC-}R_2$ | $+3ROH$ | $\leftrightarrow$ | $R\text{-OOC-}R_2$ | $+(CH2OH)_2\text{-CHOH}$ |
| \| | | | | |
| $CH_2\text{-OOC-}R_3$ | | | $R\text{-OOC-}R_3$ | |

(typically 8-22 C to 2 O)

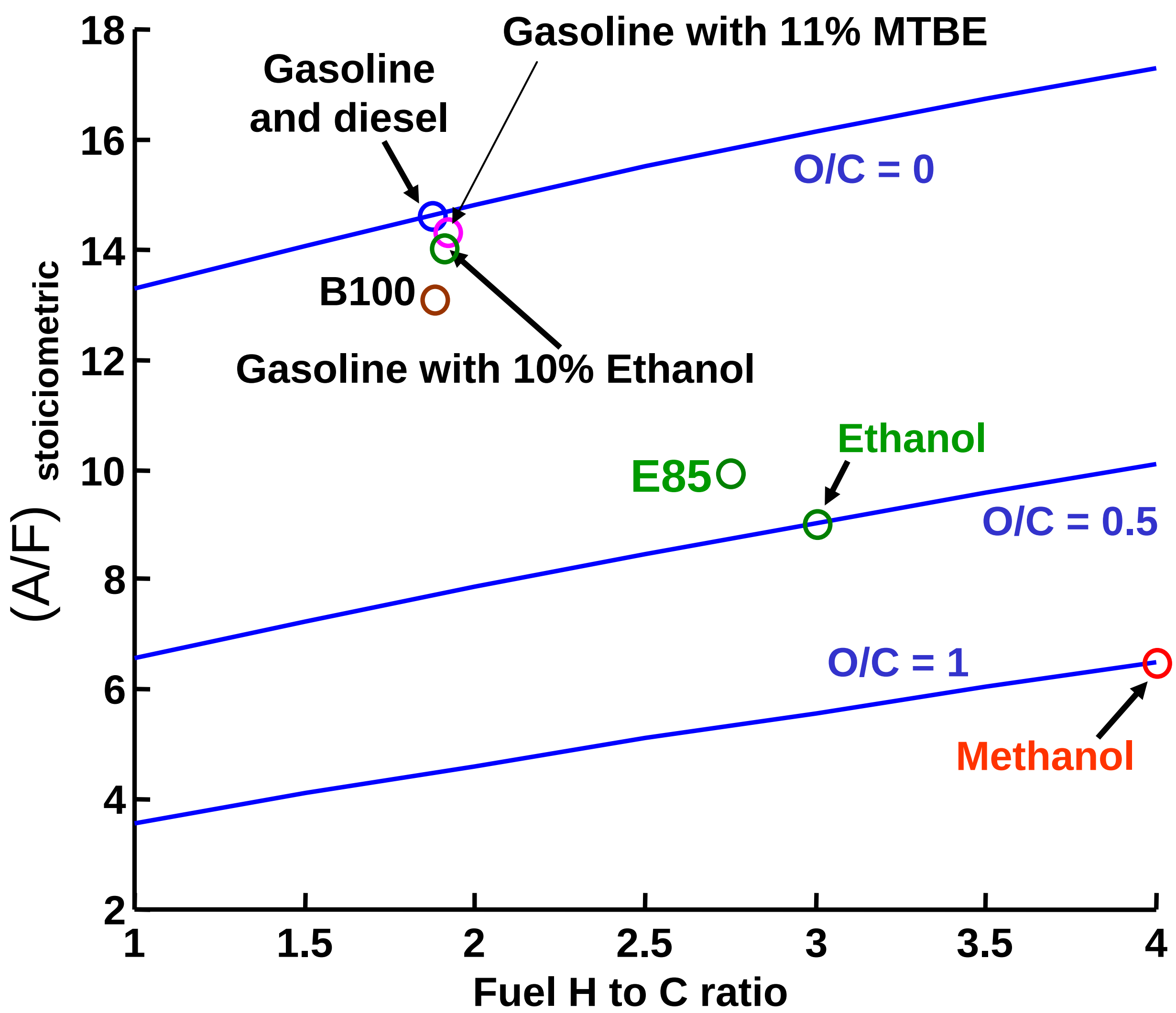
# Combustion characteristics of bio-fuel

| | **Cetane number** | s.g. | LHV (MJ/kg) | **LHV (MJ/L)** | B10 LHV (MJ/L) | B20 LHV (MJ/L) | LHV B10/ Diesel (by vol.) | LHV B20/ Diesel (by vol.) |
|---|---|---|---|---|---|---|---|---|
| **Diesel** | 45-55 | 0.820 | 43.22 | 35.44 | | | | |
| Soybean oil methylester | 50.9 | 0.885 | 37.01 | 32.76 | 35.17 | 34.91 | 0.992 | 0.985 |
| Rapeseed oil methylester | 52.9 | 0.882 | 37.30 | 32.90 | 35.19 | 34.93 | 0.993 | 0.986 |
| Sunflower oil methylester | 49 | 0.880 | 38.53 | 33.91 | 35.29 | 35.14 | 0.996 | 0.991 |
| Frying oil ethylester | 61 | 0.872 | 37.19 | 32.41 | 35.14 | 34.84 | 0.991 | 0.983 |

| | **Octane number** | s.g. | LHV (MJ/kg) | **LHV (MJ/L)** | E10 LHV (MJ/L) | E85 LHV (MJ/L) | LHV E10/ Gasoline (by vol.) | LHV E85/ Gasoline (by vol.) |
|---|---|---|---|---|---|---|---|---|
| **Gasoline** | 95 | 0.780 | 44.00 | 34.32 | | | | |
| **Ethanol** | 107 | 0.785 | 26.90 | 21.12 | 33.00 | 23.10 | 0.962 | 0.673 |

Bio-ester data from Graboski and McCormick, Prog. Energy Comb. Sc., Vol. 24, 1998

# Stoichiometric requirement for different fuels




O/C ratios of bio-diesel esters ~ 0.12

# Relative CO2 production from burning different fuel molecules

Image removed due to copyright restrictions. Please see Amann, Charles A. “The Passenger Car and The Greenhouse Effect.” *SAE Journal of Passenger Cars* 99 (October 1990): 902099.

**C. Amann, SAE Paper 9092099**

# Effects of Oxygenates on PM emission

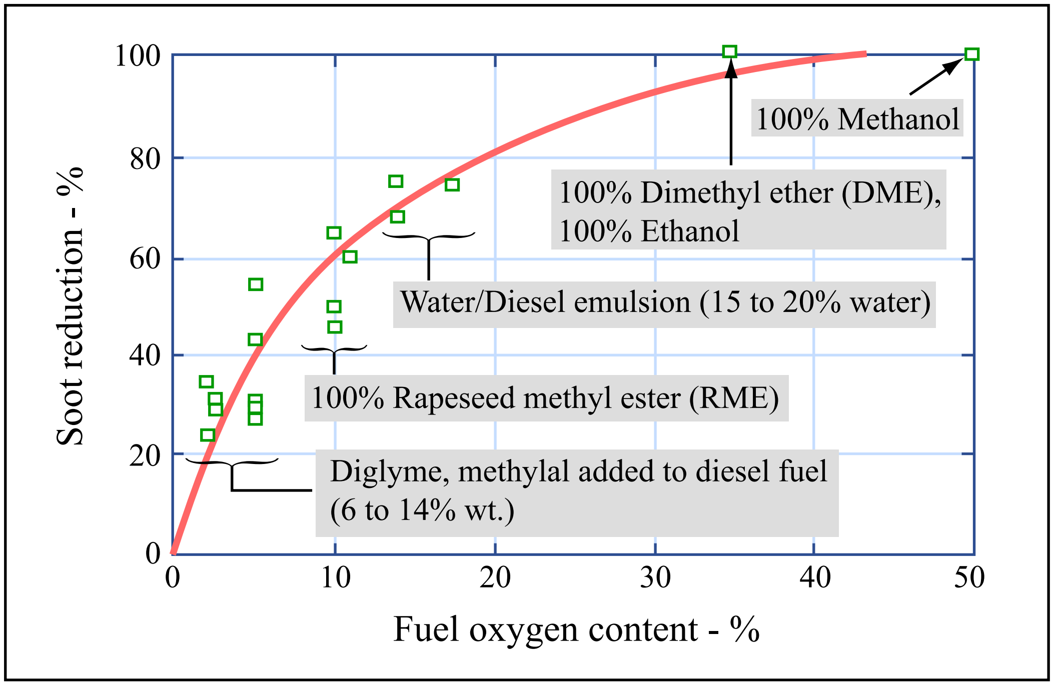



Figure by MIT OpenCourseWare.

**AVL Publication (by Wofgang Cartellieri in JSME 1998 Conference in Toykyo)**

# Bio-fuel combustion properties

- Bio-diesels and ethanol are fundamentally clean and attractive fuels to be used in engines
- The use of these fuels as supplements to petroleum base fuel are compatible with current engine configuration and fuel infra-structure
- Practical issues can be adequately handled by engineering
  - Fuel quality
  - Engine calibration
  - Materials compatibility, viscosity, …

**Burning the fuel is the least of the problem !!!**

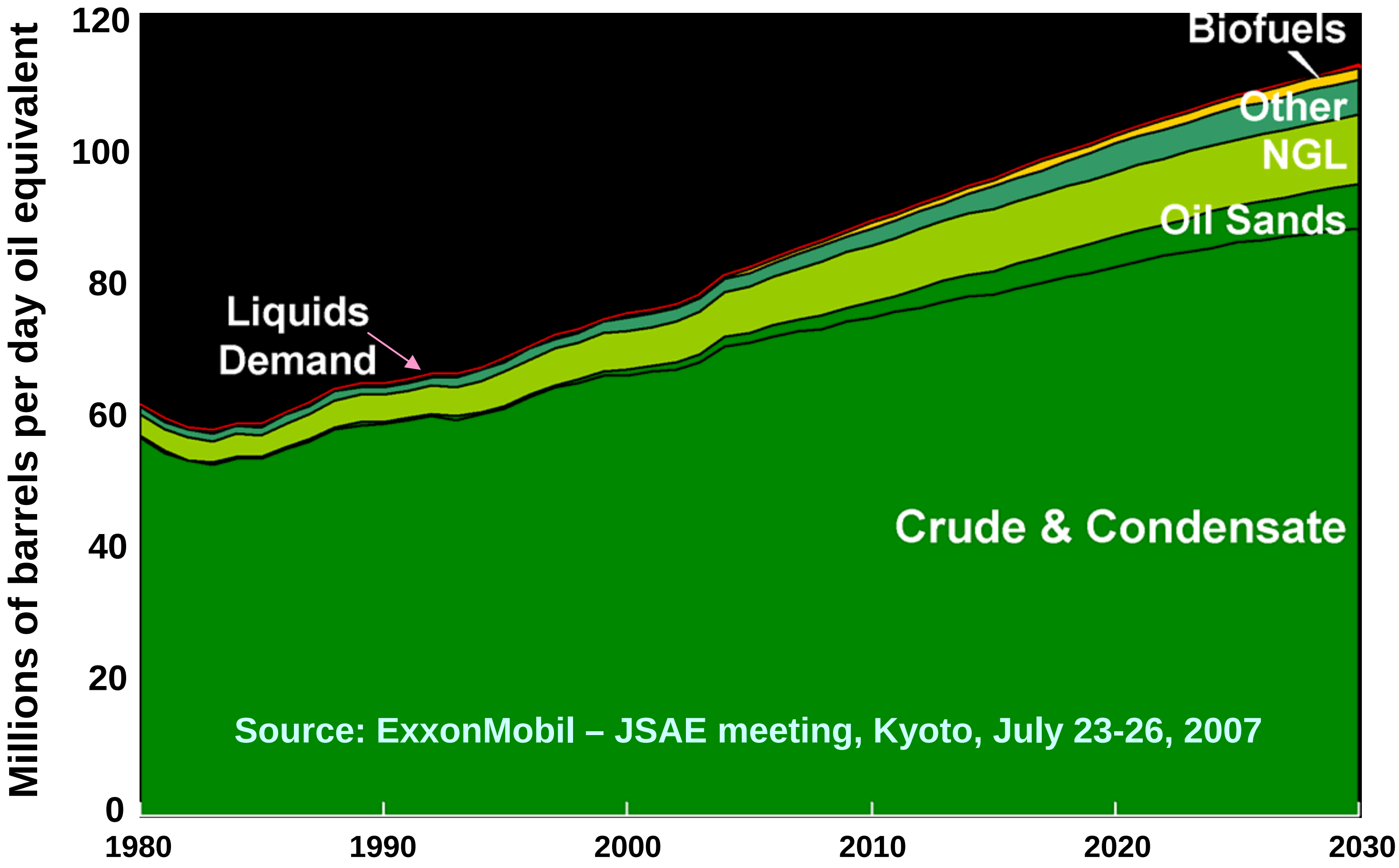
## Status of bio-fuel production

# World liquid fuel production (2005)

**HYDROCARBONS** **RENEWABLES**

Image removed due to copyright restrictions. Please see p. 2 in Budny, Daniel. "The Global Dynamics of Biofuels." Brazil Institute Special Report. Washington, DC: Woodrow Wilson International Center for Scholars, April 2007.

# Liquid fuel supply projection



# US bio-fuel capacity

**US biofuels**

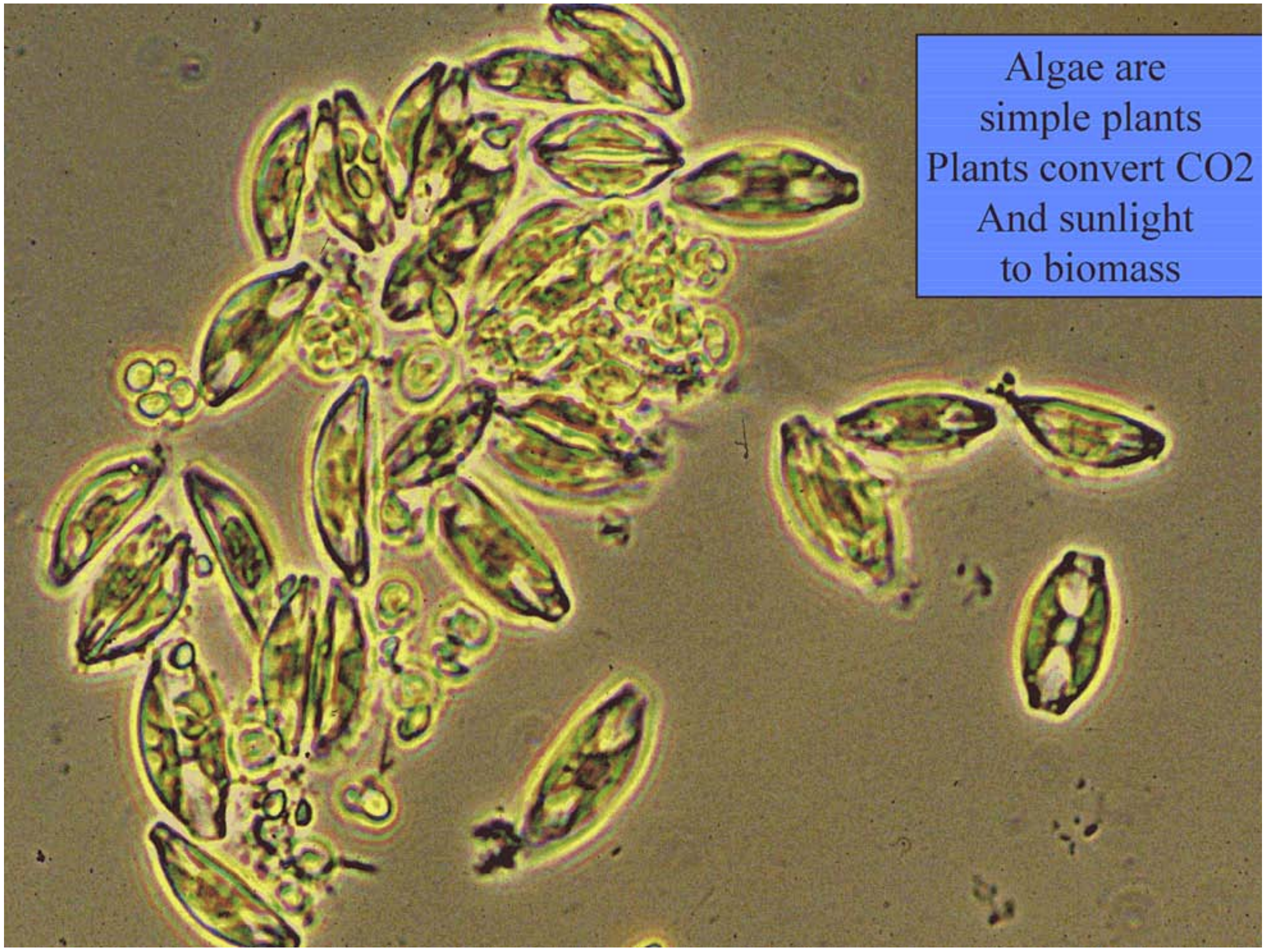
| | |
|---|---|
| US harvested crop land (US agriculture census 2002), hectare | **1.23E+08** |
| US all distillate use (diesel+jet+power gen etc.) EIA2007; L/yr | 3.34E+11 |
| US gasoline use, EIA 2007; L/yr | 5.40E+11 |

| | **gal/acre** | **L/hectare** | **Limit of production (gal)** | **Limit of production (L)** | **Energy ratio of limit to demand** |
|---|---|---|---|---|---|
| **bio-diesel** | | | | | |
| palm oil | 5.08E+02 | 4,756 | 1.54E+11 | 5.85E+11 | **1.63** |
| coconut | 2.30E+02 | 2,153 | 6.99E+10 | 2.65E+11 | **0.74** |
| rapeseed | 1.02E+02 | 955 | 3.10E+10 | 1.17E+11 | **0.33** |
| soy | 6.00E+01 | 562 | 1.82E+10 | 6.91E+10 | **0.19** |
| peanut | 9.00E+01 | 843 | 2.73E+10 | 1.04E+11 | **0.29** |
| sunflower | 8.20E+01 | 768 | 2.49E+10 | 9.44E+10 | **0.27** |
| jatropia (SE Asia) | 2.00E+02 | 1,872 | 6.08E+10 | 2.30E+11 | **0.64** |
| algae (?) | 1.80E+03 | 16,850 | 5.47E+11 | 2.07E+12 | **5.78** |
| | | | | | |
| **ethanol** | | | | | |
| corn | 3.44E+02 | 3,217 | 1.04E+11 | 3.96E+11 | **0.71** |
| sugar cane (Brazil) | 8.00E+02 | 7,489 | 2.43E+11 | 9.21E+11 | **1.71** |

**Crop based bio-fuels do not have enough capacity to meet the liquid fuel demand !!!**

Yield dependent on location and weather

# Algae: micro-seaweeds




Courtesy of Robert Dibble. Used with permission.

## Issues

- Production
  - Need high lipid content species
  - Need fast growth species
  - Growth in dense environment
- Harvest techniques
- Oil extraction

## Current largest algae plant
## (production of algae for salmon feeding)

Hawaii

Courtesy of Robert Dibble. Used with permission.

# Sustainability

**Energy balance**
**Example: Corn ethanol in US**

## Ethanol from corn

- Several studies of the overall energy budget
  - P = energy used in production
    - feedstock production/ transport + processing
  - E = Energy of the ethanol output
  - Return (%) = (E – P) / E
- **Studies**
  - Pimentel and Patzek (2003, 2005): **negative return**
    - Return = **- 29%**
  - USDA (Shapouri et al 2002, 2004): **positive return**
    - Return* = **+5.6%**
    - Return* = **+40%** if by products (Corn gluten meal, etc.) are accounted for

**Verdict: Substantial environmental and economic cost; return not clear**

*** For comparison purpose, these figures were converted from the values of (E-P)/P of +5.9% and +67% in the original publication**

# Other bio-fuels

- Pimentel and Patzek also estimated energy budget for other bio-fuels. Returns:
  - Ethanol from switchgrass = -50%
  - Ethanol from wood biomass = -57%
  - Bio-diesel from  soybean = -27%
  - Bio-diesel from sunflower = -118%
- Other more positive estimates:
  - Bio-diesel from rapeseed = +32% (EU)
  - Bio-diesel production = +324% (US National Bio-diesel Board)

- Outlook: NOT CLEAR
  - New technology needed to change the picture

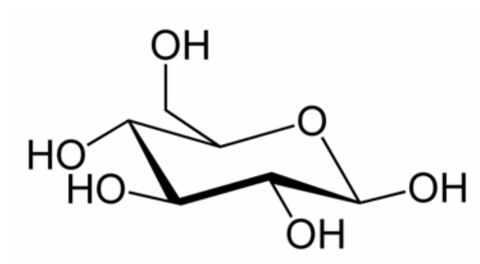
# Technical difficulties of producing liquid fuel from plants

- Glucose fermentation produces significant CO2 out and energy loss

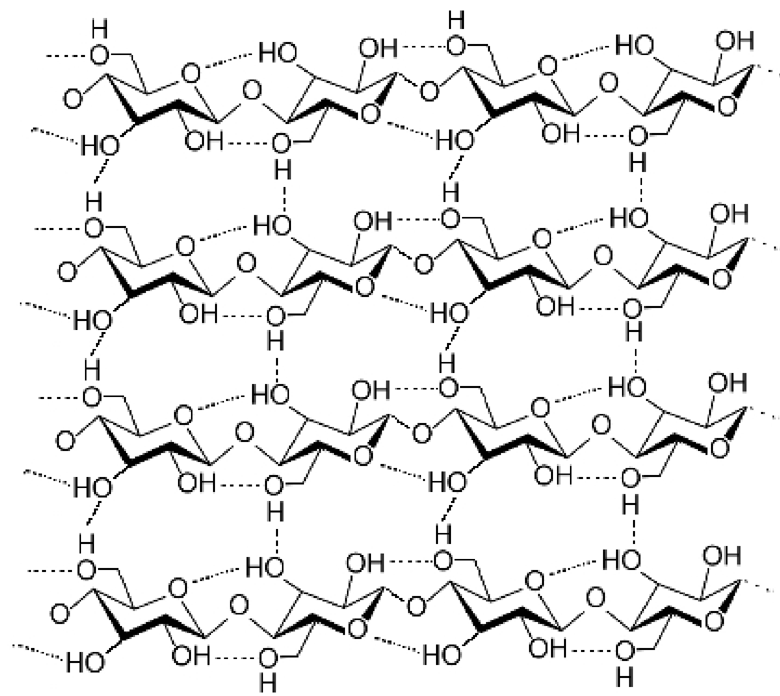
$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 + 219.2\ KJ$$

**$\Delta H_f$ per mol of carbon atom:** **-67.8 KJ** **-117.3 KJ** **- 393.5 KJ**

- Cellulose much more difficult to break down than sugar



**Glucose**



**Cellulose**

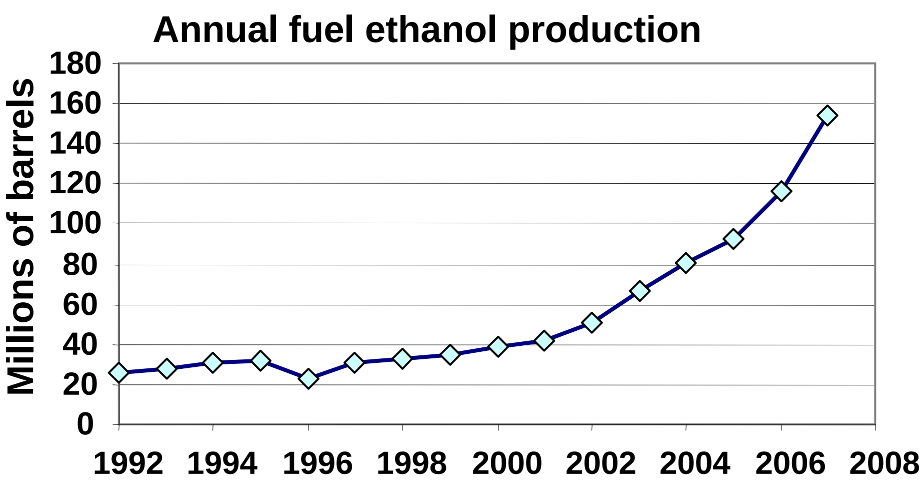
Source: Wikipedia

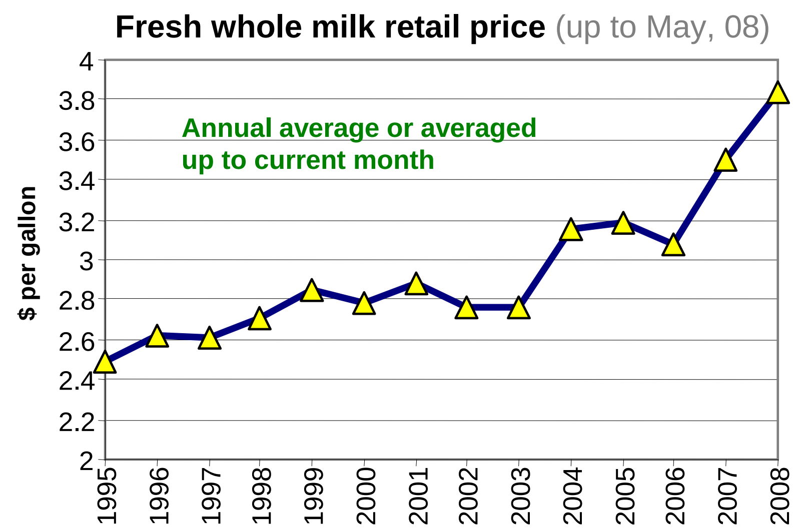
## Effect of government policy on bio-fuel

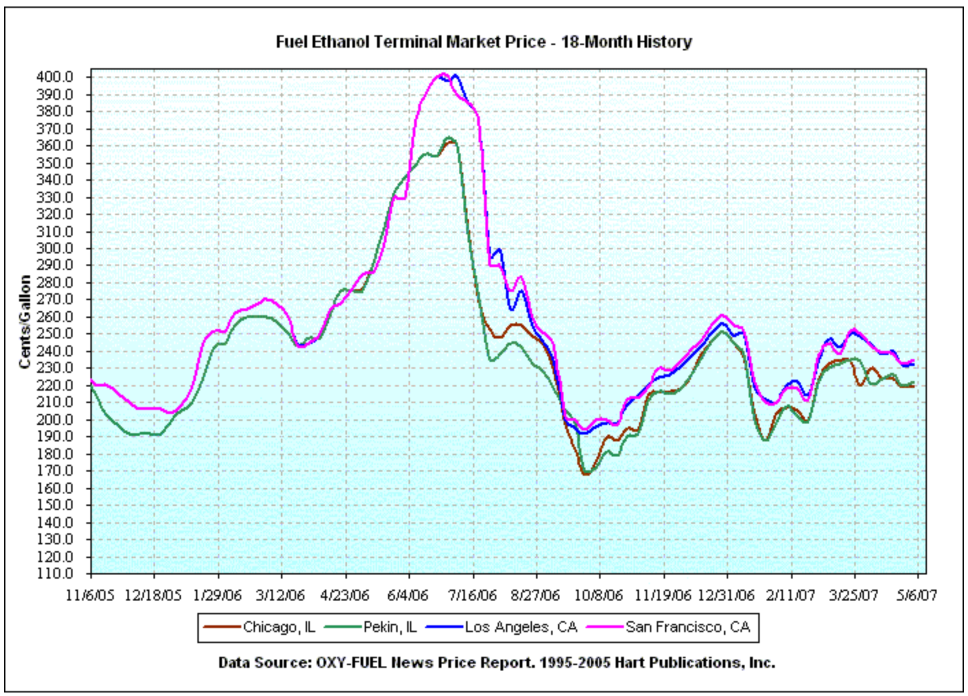
- Current US demand for ethanol is driven by government regulations and incentives
  - Ethanol flex-fuel vehicles produced because of the 74% credit towards CAFE requirement
    - **(E85 vehicle equivalent mph = mpg x 1.74)**
  - Gasoline oxygenate mandate, and phase out of MTBE
  - Energy bill (Aug. 05) mandated a threshold of 7.5 billion gallons (180 million barrels) production by 2012
  - Tax subsidy
    - blender's tax credit $0.51/gallon alcohol
    - $0.051/gallon fuel tax exemption for gasohol
      - minimum 10 vol % alcohol

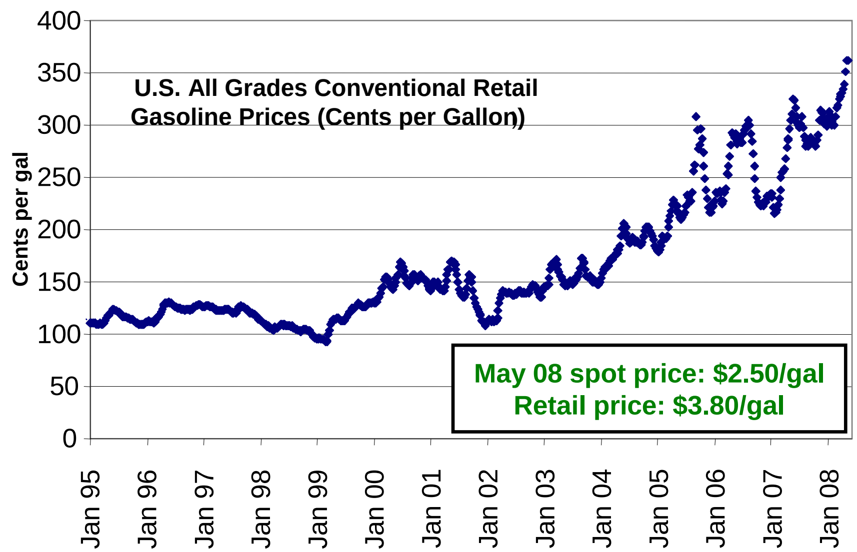
# Economic impact of crop-based bio-fuel

**Example: Corn ethanol in US (~20% of total corn production in 2007)**



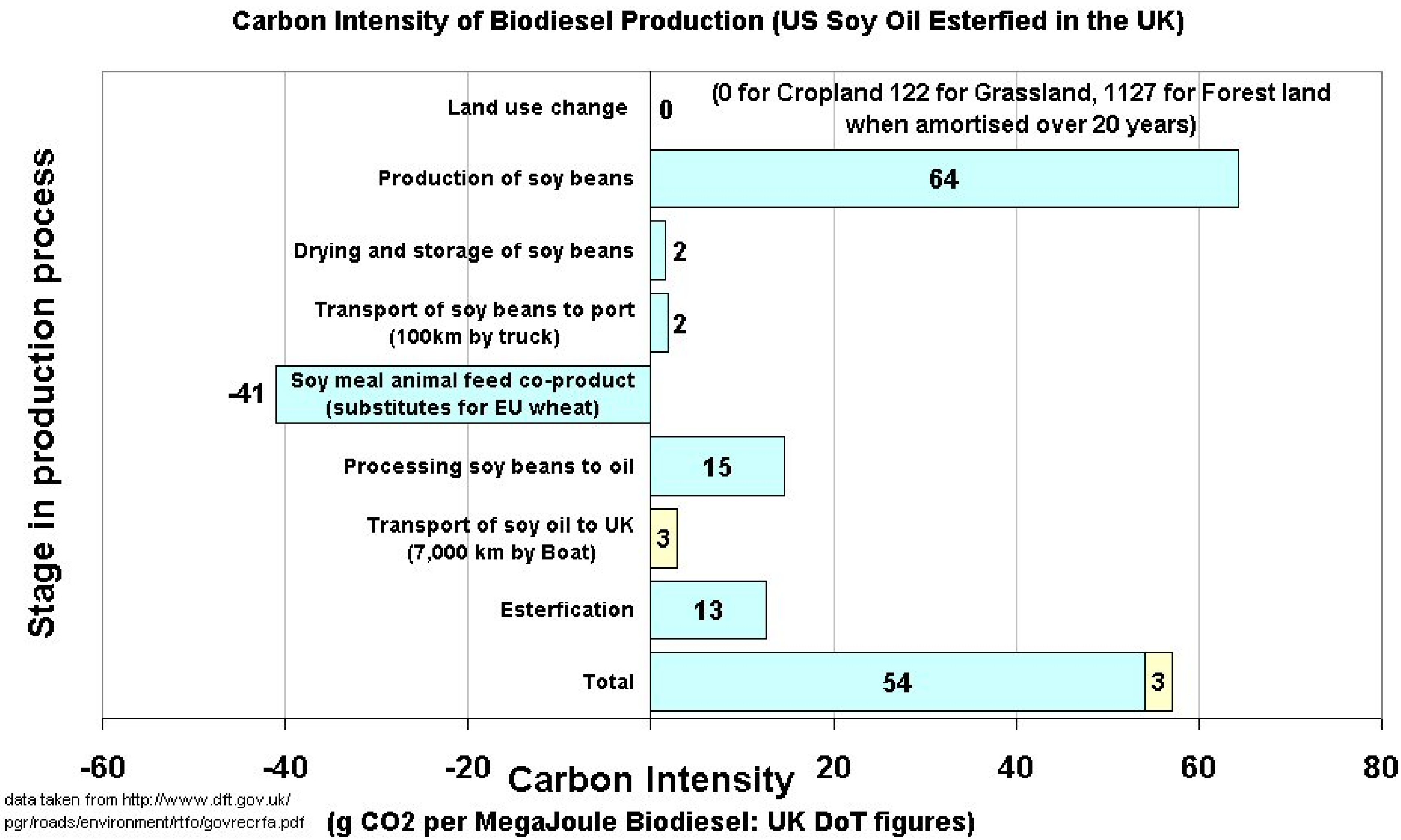



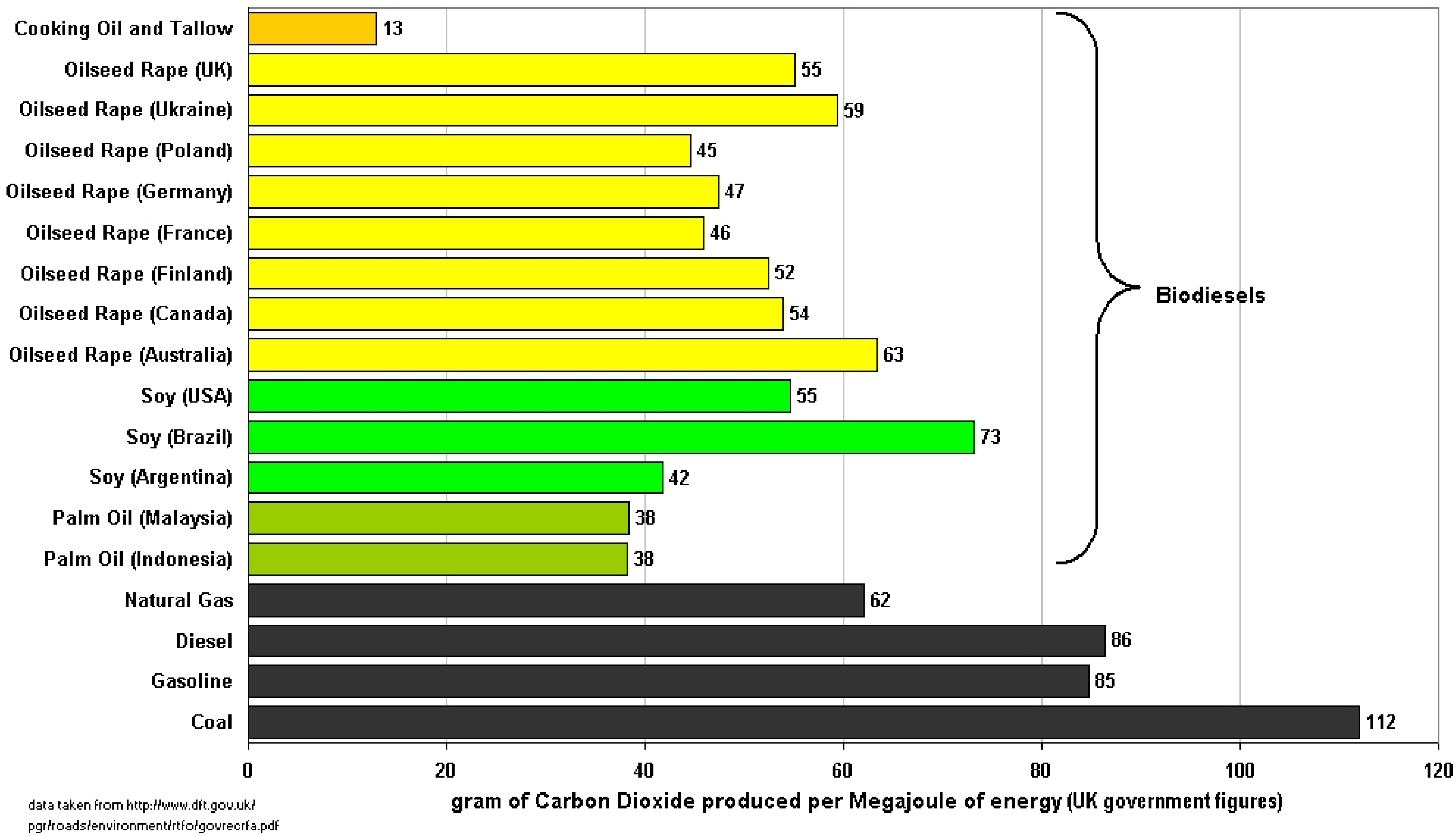

Source: California Energy Commission, 2006

# Carbon intensity
## (net mass of CO2 produced per unit fuel energy)




Source: http://en.wikipedia.org/wiki/Biodiesel

# Carbon intensity




Source: http://en.wikipedia.org/wiki/Biodiesel

## Other environmental impact

- Water resources
- Fertilizer
- Soil
- Bio-diversity
- Plant waste treatment

# Closure

- Bio-diesel and alcohols are excellent fuels for transportation use
  - Good combustion characteristics
  - Compatible with current engine technology
- Sustainability
  - Bio-fuels from crops are not likely to make any significant impact on the global liquid fuel supply picture
    - Land capacity
    - Effect on food price
  - Further development on other feed stocks needed
    - Algae for bio-diesel production
    - Cellulosic alcohol

## Closure (continue)

- Sustainability issues
  - Energy budget
  - Water use
  - $CO_2$ intensity especially with land use replacement
  - Bio-diversity
  - Other issues
    - ➢Bio-fuel plant waste treatment
    - ➢Resources requirement

# Hybrid vehicles

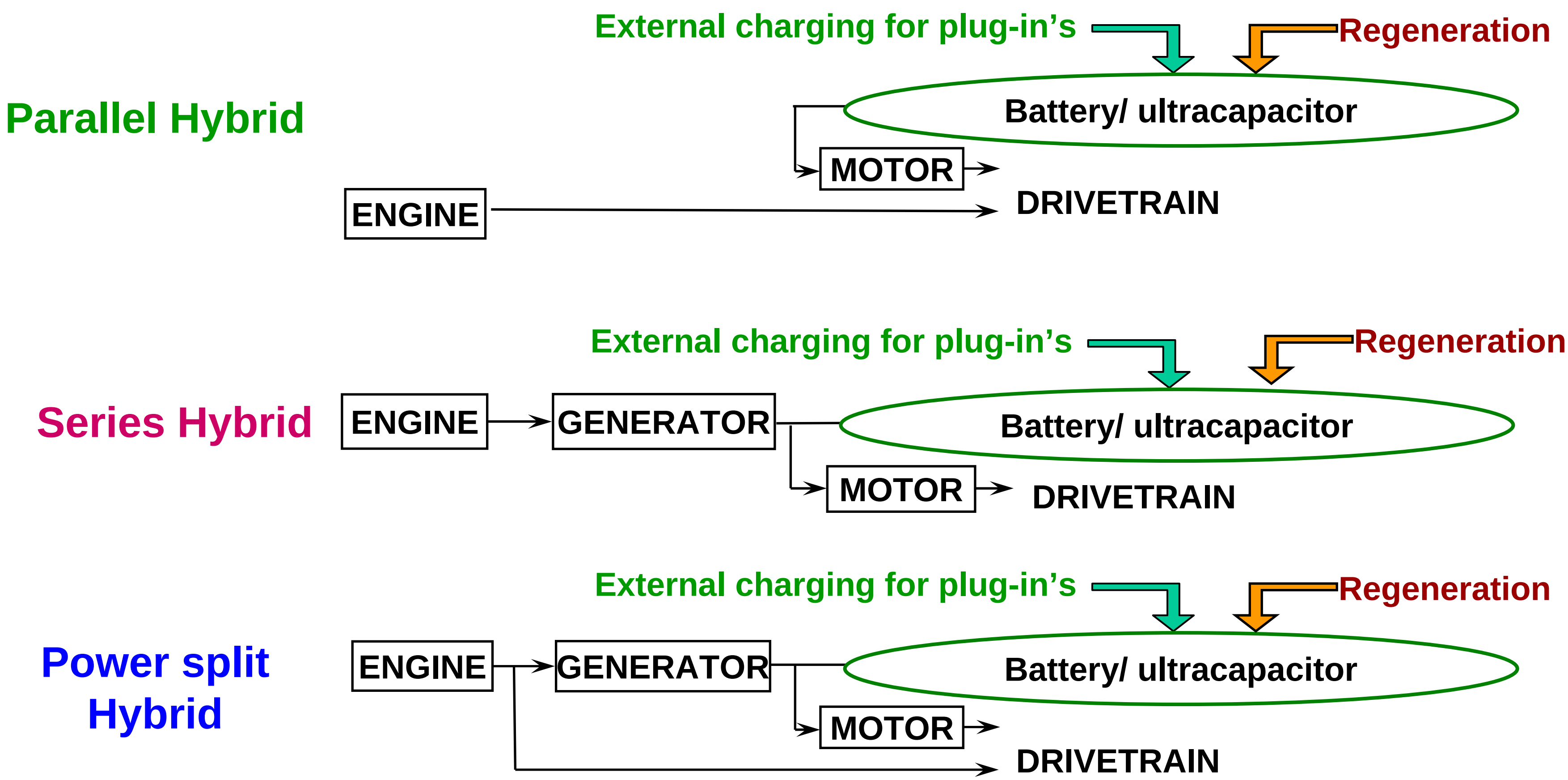
## Configuration:

IC Engine + Generator + Battery + Electric Motor

## Concept

- Eliminates external charging
- As “load leveler”
    - Improved overall efficiency
- Regeneration ability
- Plug-in hybrids: use external electricity supply

# Hybrid Vehicles




**Examples:** **Parallel hybrid: Honda Insight**
**Series hybrid: GM E-Flex System**
**Power split hybrid: Toyota Prius**

# Hybrids and Plug-in hybrids

Hybrids (HEV)

- "Stored fuel centered"
  - Full hybrid
  - Mild hybrid /power assist

Plug-in hybrids (PHEV)

- "Stored electricity centered"
  - Blended PHEV
  - Urban capable PHEV
  - AER/ E-REV

## Engine/ motor sizing

Images removed due to copyright restrictions. Please see Fig. 14 in Komatsu, Masayuki, et al. "Study on the Potential Benefits of Plug-In Hybrid Systems." *SAE International Journal of Passenger Cars - Electronic and Electrical Systems* 1 (April 2008): 2008-01-0456.
and
Fig. 8 in Tate, E. D., Michael O. Harpster, and Peter J. Savagian. "The Electrification of the Automobile: From Conventional Hybrid, to Plug-In Hybrids, to Extended-Range Electric Vehicles." *SAE International Journal of Passenger Cars - Electronic and Electrical Systems* 1 (April 2008): 2008-01-0458.

**The optimal component sizing and power distribution strategy depend on the required performance, range, and drive cycle**

The reduced load/ speed dynamic range required from the engine offers design opportunities

Image removed due to copyright restrictions. Please see Fig. 3 in Aoki, Kaoru, et al.
"Development of an Integrated Motor Assist Hybrid System: Development of the 'Insight', a Personal Hybrid Coupe."
*SAE Journal of Engines* 109 (June 2000): 2000-01-2216.

## Toyota Prius

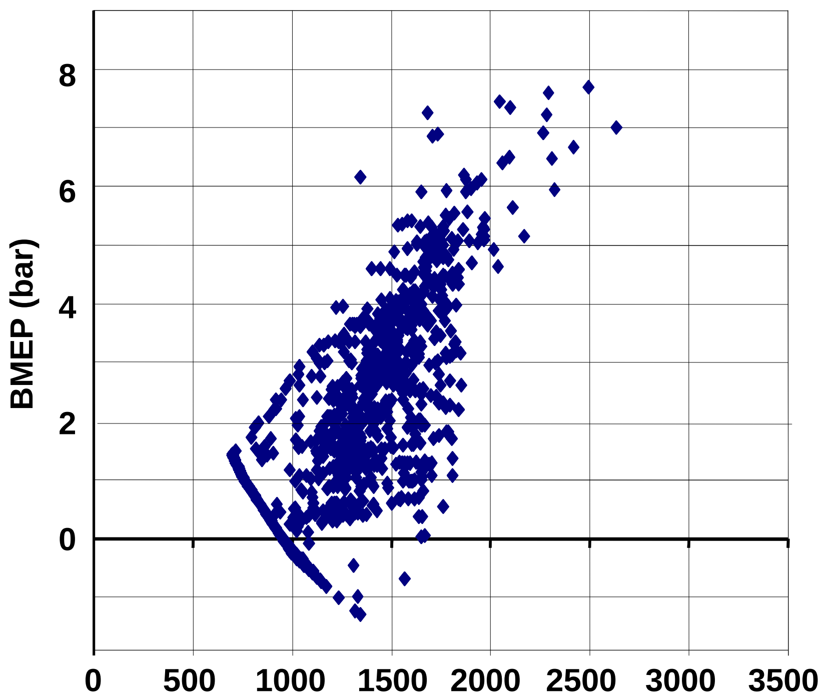
- Engine: 1.5 L, Variable Valve Timing, Atkinson/Miller Cycle (13.5 expansion ratio), Continuously Variable Transmission
  - 57 KW at 5000 rpm
- Motor - 50 KW
- Max system output – 82 KW
- Battery - Nickel-Metal Hydride, 288V; 21 KW
- Fuel efficiency:
  - 66 mpg (Japanese cycle)
  - 43 mpg (EPA city driving cycle)
  - 41 mpg (EPA highway driving cycle)
- Efficiency improvement (in Japanese cycle) attributed to:
  - 50% load distribution; 25% regeneration; 25% stop and go
- Cost: ~$20K

# Efficiency improvement: Toyota Hybrid System (THS)

Image removed due to copyright restrictions. Please see Fig. 2 in Inoue, Toshio, et al. "Improvement of a Highly Efficient Hybrid Vehicle and Integrating Super Low Emissions." *SAE Journal of Fuels and Lubricants* 109 (October 2000): 2000-01-2930.

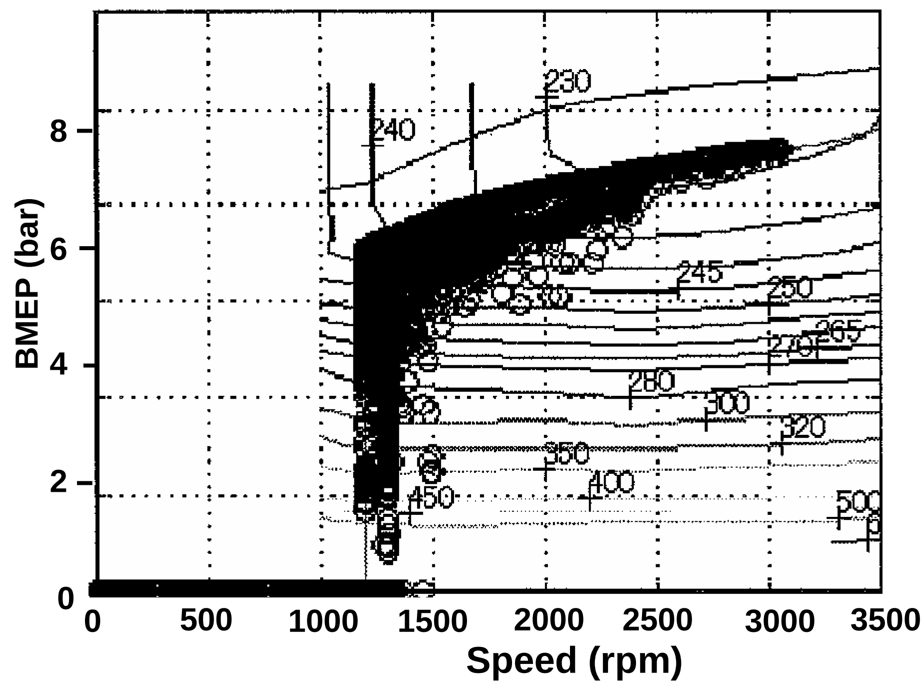
# Operating map in LA4 driving cycle

Typical passenger car engine




Toyota THS II

Data from SAE 2004-01-0164



# Cost factor

If $\Delta\$$ is price premium for hybrid vehicle
P is price of gasoline (per gallon)
$\delta$ is fractional improvement in mpg

Then mileage (M) to be driven to break even is

$$M = \frac{\Delta\$ \text{ x mpg}}{P \text{ x } \delta}$$

**(assume that interest rate is zero)**

# Cost Factor

Example:

Honda Civic and Civic-Hybrid

Price premium ($\Delta$\$, MY08 listed) = \$7155 **(\$22600-15445)**
mpg (city and highway av.) = 29 mpg (42 for hybrid)
hybrid improvement in mpg(%) = 45%

At gasoline price of \$4.00 per gallon, mileage (M) driven to break even is

$$M = \frac{\$7155 \times 29}{\$4 \times 45\%} = 115{,}000 \text{ miles}$$

**(excluding interest cost)**

# Barrier to Hybrid Vehicles

- Cost factor
  – difficult to justify especially for the small, already fuel efficient vehicles
- Battery replacement **(not included in the previous breakeven analysis)**
  – California ZEV mandate, battery packs must be warranted for 15 years or 150,000 miles : a technical challenge

# Hybrid Vehicle Outlook

- Hybrid configuration will capture a fraction of the passenger market, especially when there is significant fuel price increase
- Competition
  - Customers downsize their cars
  - Small diesel vehicles
- Plug-in hybrids?
  - Weight penalty (battery + motor + engine)
  - No substantial advantage for overall $CO_2$ emissions
  - Limited battery life

# Sales figure for hybrid vehicles