Internal Combustion Engines: The Worst Form of Vehicle Propulsion - Except for All the Other Forms

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Download this presentation:

http://ronney.usc.edu/WhyICEngines.zip

Outline

- Introductions
  - Personal
  - To this subject
- Some remarks about US and global energy / environmental trends
- Definition of Internal Combustion Engines (ICEs)
- Types of ICEs
- History and evolution of ICEs
- Things you need to know before…
- What are the alternatives?
- Practical perspective

- (Optional) engine lab tour – 9:15 am tomorrow (Friday) morning, meet at OHE elevators, lab is in OHE basement

Introduction

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- Hydrocarbon-fueled ICEs are the power plant of choice for vehicles in the power range from 5 Watts to 100,000,000 Watts, and have been for over 100 years
- 200 million ICEs are built every year, ≈ 1.5x the human birth rate
- There is an unlimited amount of inaccurate, misleading and/or dogmatic information about ICEs
- This seminar's messages
  - Why ICEs are so ubiquitous
  - Why it will be so difficult to replace them with another technology
  - What you will have to do if you want to replace them
- Ask questions, challenge me and each other – discussion is more important than lecture

Topic for discussion

Our current energy economy, based primarily on fossil fuel usage, evolved because it provided the best value (convenience). Is it possible that it's also the most environmentally responsible (or “least environmentally irresponsible”) system?

US energy usage

- > 80% of world energy production results from combustion of fossil fuels
- Energy sector accounts for 9% of US Gross Domestic Product
- Our continuing habit of burning things and our quest to find more things to burn has resulted in
  - Economic booms and busts
  - Political and military conflicts
  - Deification of oil - “the earth’s blood”
  - Global warming (or the need to deny its existence)
  - Human health issues

Global warming

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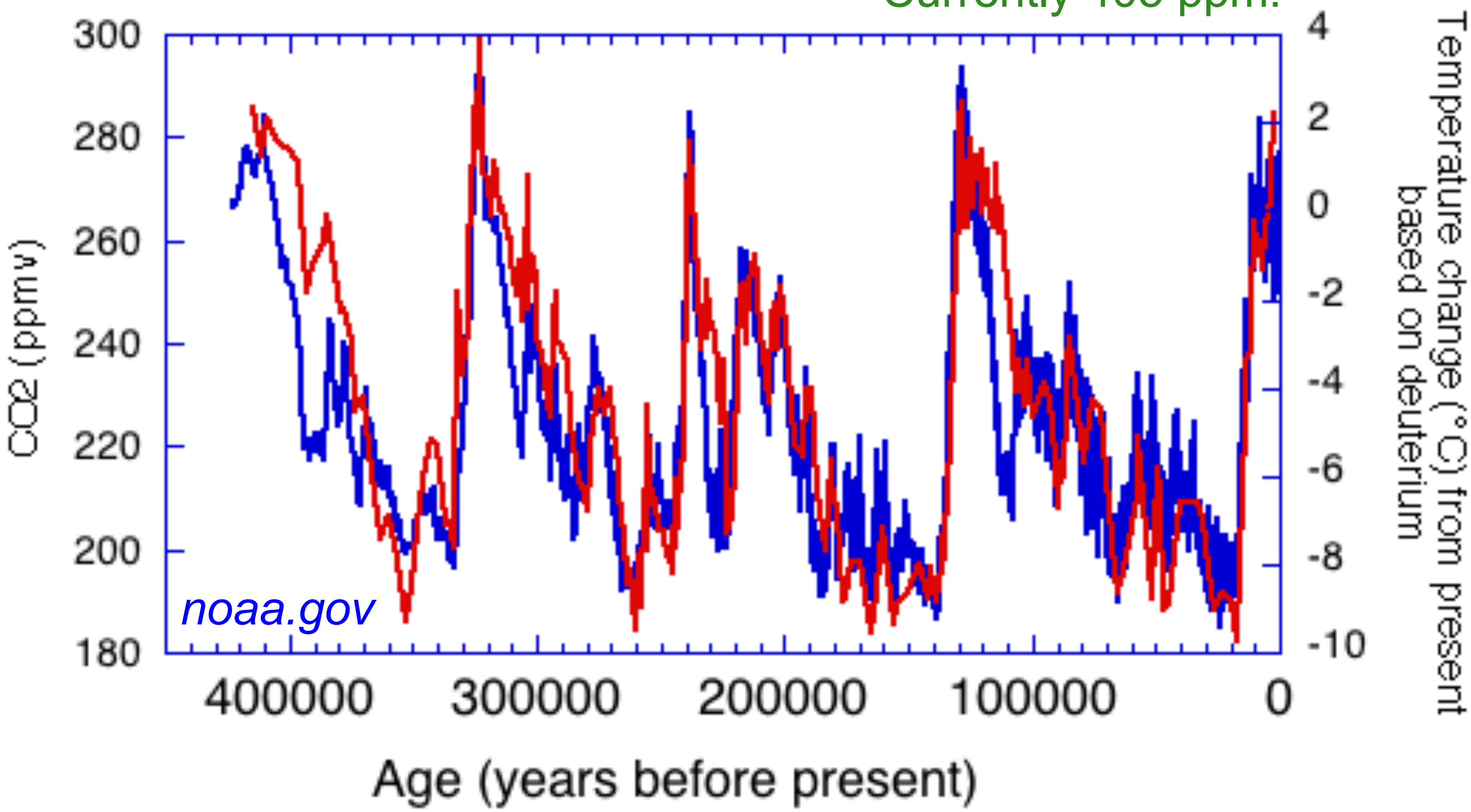
- Intergovernmental Panel on Climate Change (> 800 scientists selected from > 3500 nominations) in 2013 http://www.ipcc.ch/report/ar5/wg1/

"It is extremely likely [>95%] that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together"

Currently 405 ppm!



Global warming

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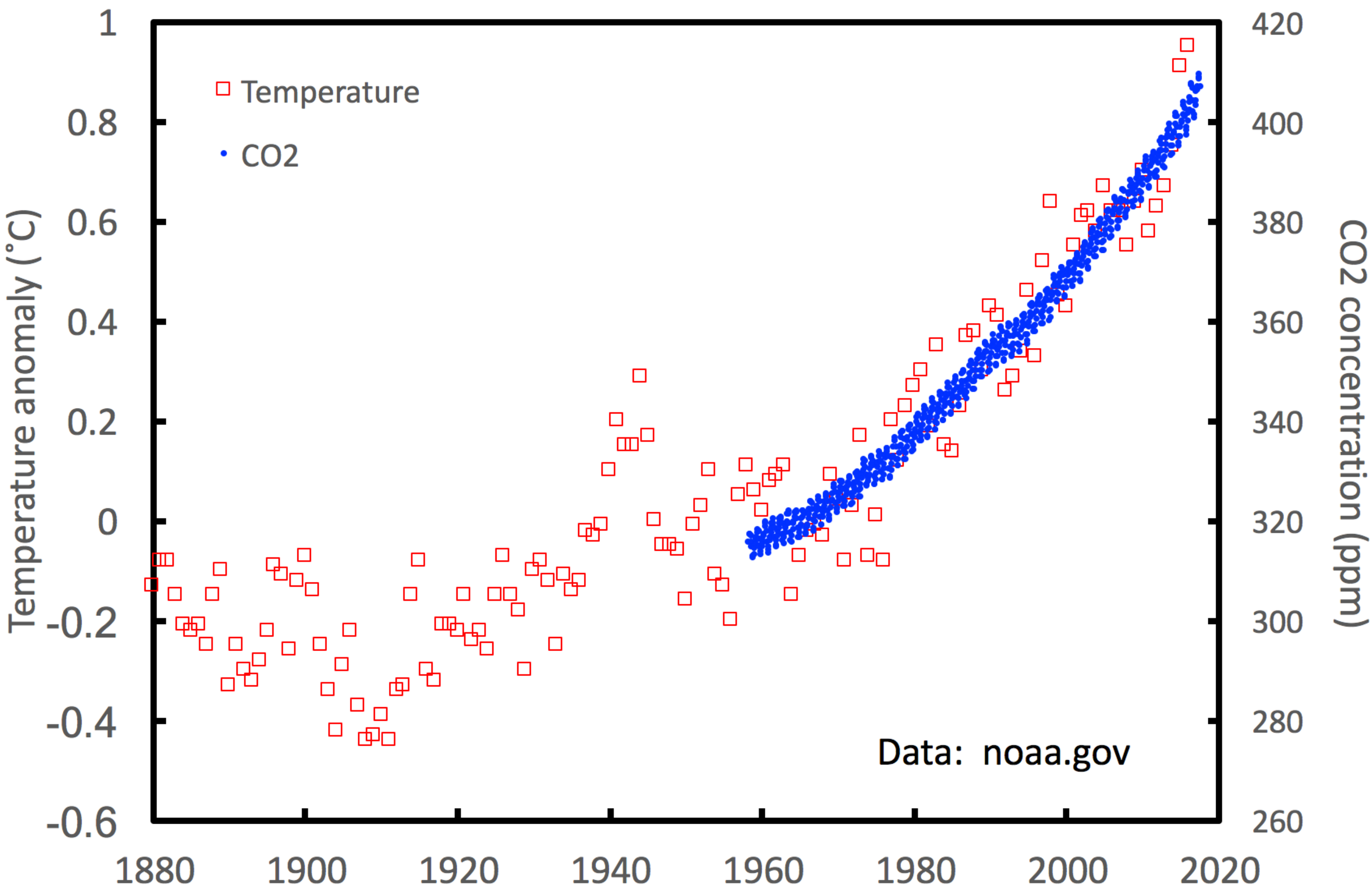

US energy flow, 2011, units 10^{15} BTU/yr

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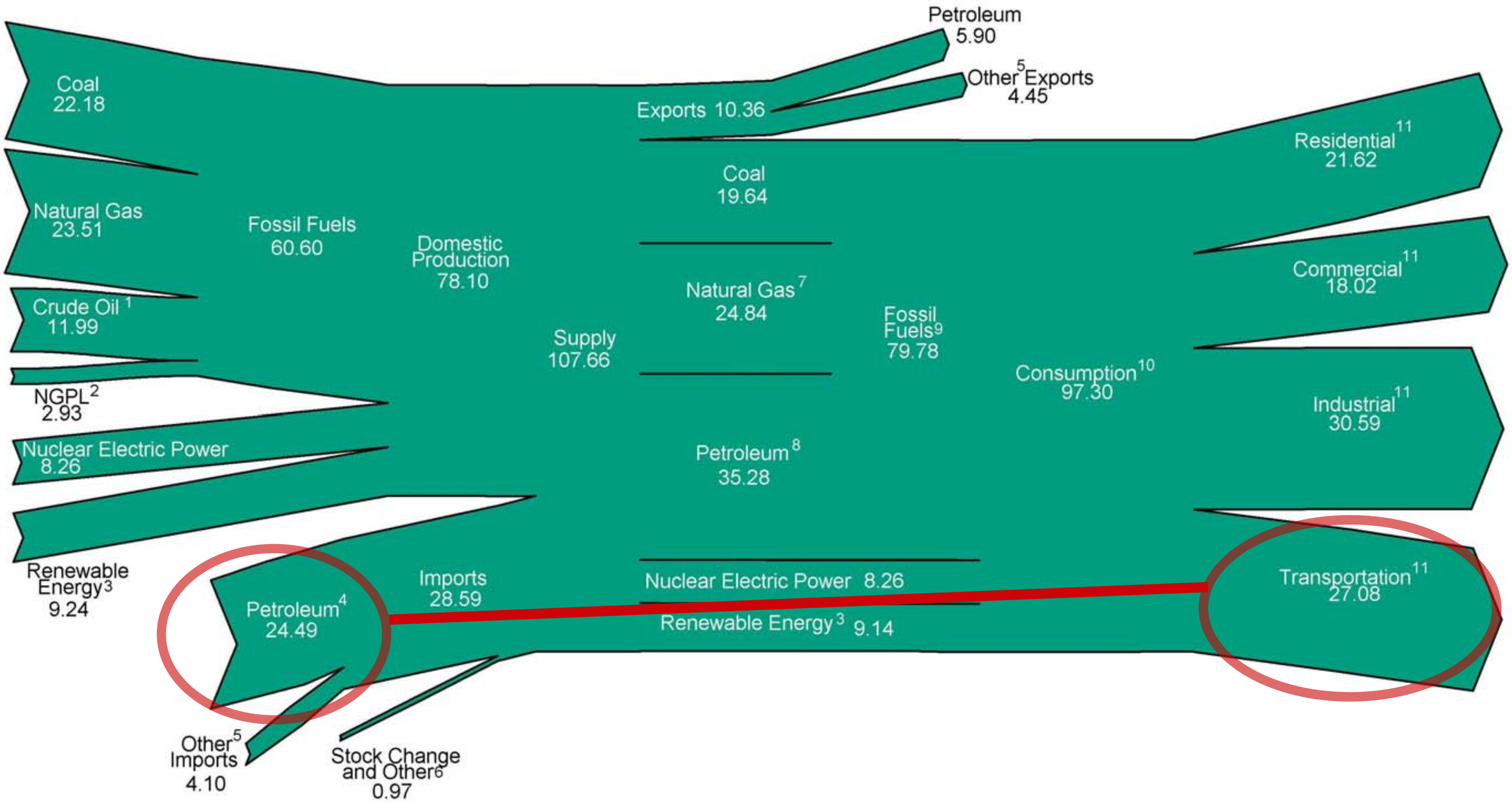


Each 10^{15} BTU/yr = 33.4 gigawatts

http://www.eia.gov/totalenergy/data/annual/diagram1.cfm

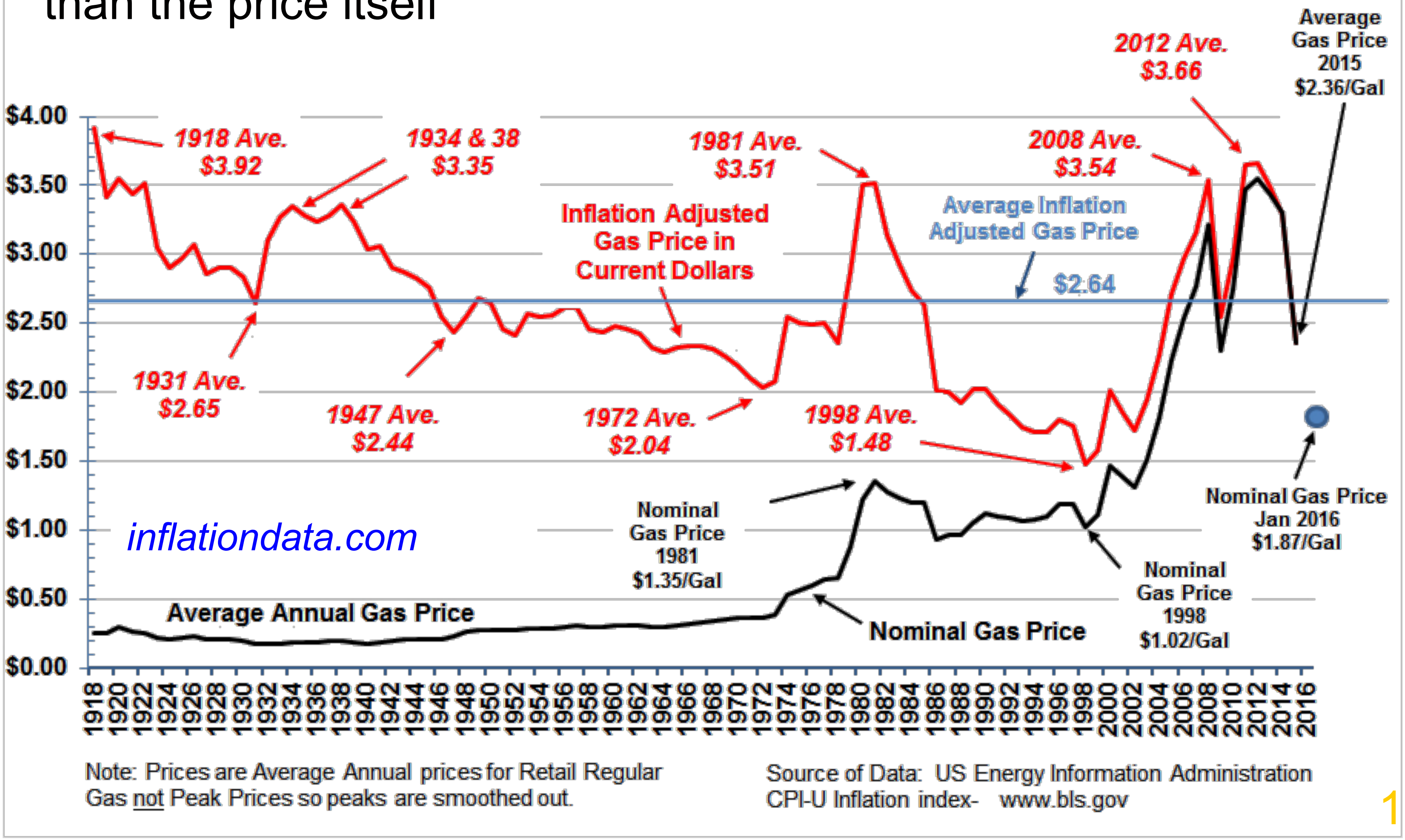
US energy demand

2.25 gigawatt coal power plant (Page, AZ), 34% coal-to-electricity efficiency

US total energy demand (not just electrical) ≈ 490 of these, running continuously 24/7

Inflation-adjusted gasoline prices

- $2.64/gal ± 50% for last 100 years
- Even during energy “crises” prices didn’t change that much
- The public is much more sensitive to the <u>rate</u> of change in price than the price itself



Classification of ICEs

- Definition of an ICE: a heat engine in which the heat source is a combustible mixture that also serves as the working fluid
- The working fluid in turn is used either to
  - Produce shaft work by pushing on a piston or turbine blade that in turn drives a rotating shaft or
  - Creates a high-momentum fluid used directly for propulsive force

Is an ICE

- Gasoline-fueled reciprocating piston engine
- Diesel-fueled reciprocating piston engine
- Gas turbine
- Rocket

Is not an ICE

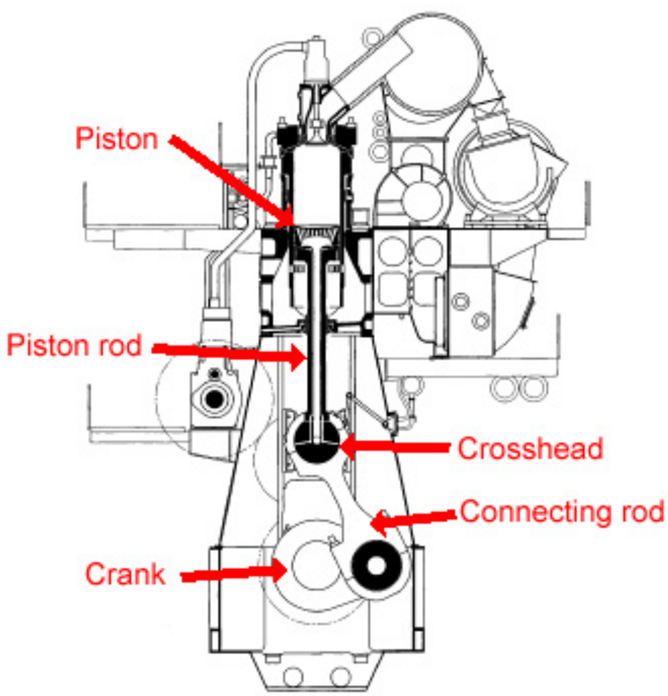
- Steam power plant
- Solar power plant
- Nuclear power plant

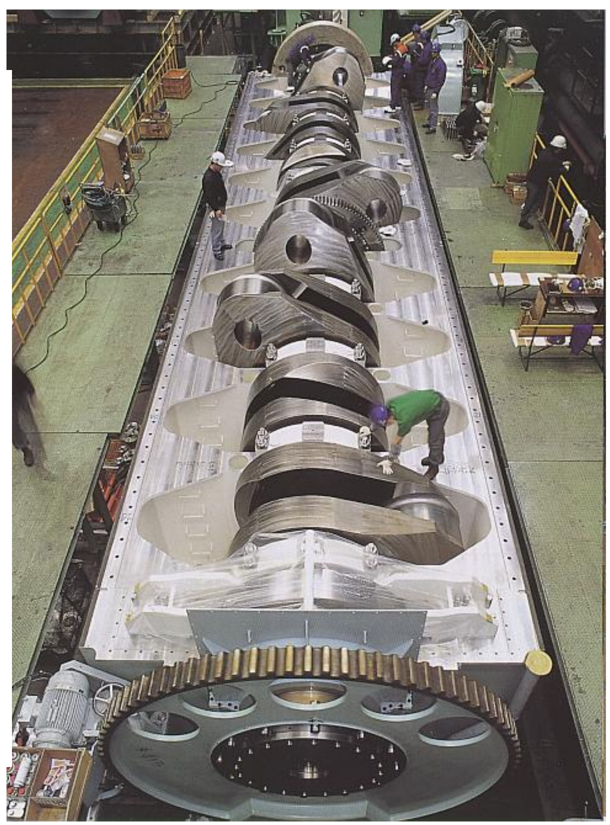
ICE family tree

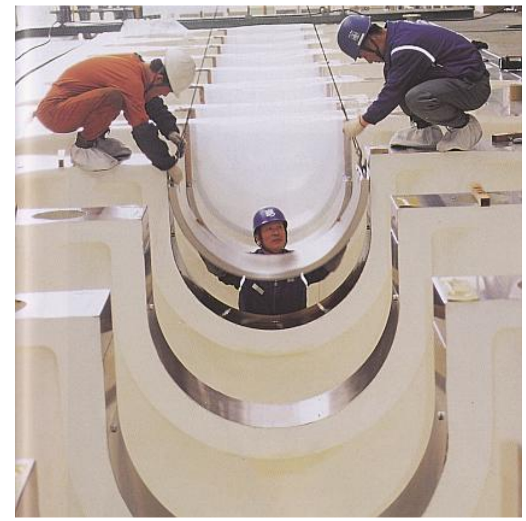
- **Internal Combustion Engines**
  - **Steady**
    - **Gas Turbine** – Uses compressor and turbine, not piston-cylinder
      - **Turboshaft** – All shaft work to drive propeller, generator, rotor (helicopter)
      - **Turbofan** – Part shaft, part jet - "ducted propeller"
      - **Turbojet** – All jet except for work needed to drive compressor
    - **Ramjet** – No compressor or turbine. Use high Mach no. ram effect for compression
    - **Rocket** – Carries both fuel and oxidant. Jet power only, no shaft work
      - **Solid fuel** – Fuel and oxidant are premixed and put inside combustion chamber
      - **Liquid fuel** – Fuel and oxidant are initially separated and pumped into combustion chamber
  - **Non-steady**
    - **Premixed-charge** – Fuel and air are mixed before/during compression. Usually ignited with spark after compression
      - **Two-stroke** – One complete thermodynamic cycle per revolution of engine
      - **Four-stroke** – One complete thermodynamic cycle per two revolutions of engine
    - **Non-premixed charge** – Only air is compressed, fuel is injected into cylinder after compression
      - **Two-stroke** – One complete thermodynamic cycle per revolution of engine
      - **Four-stroke** – One complete thermodynamic cycle per two revolutions of engine

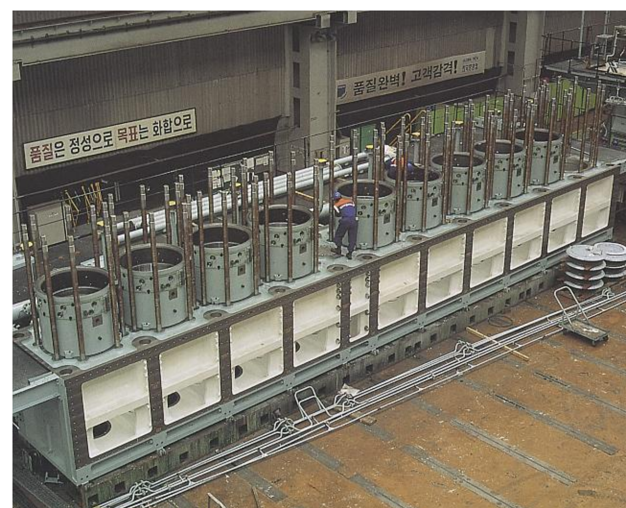
Largest internal combustion engine

- Wartsila-Sulzer RTA96-C turbocharged two-stroke diesel, built in Finland, used in container ships
- 14 cyl. version: weight 2300 tons; length 89 feet; height 44 feet; max. power 108,920 hp @ 102 rpm; max. torque 5,608,312 ft lb @ 102 RPM
- Power/weight = 0.024 hp/lb
- Also one of the most efficient IC engines: 51%



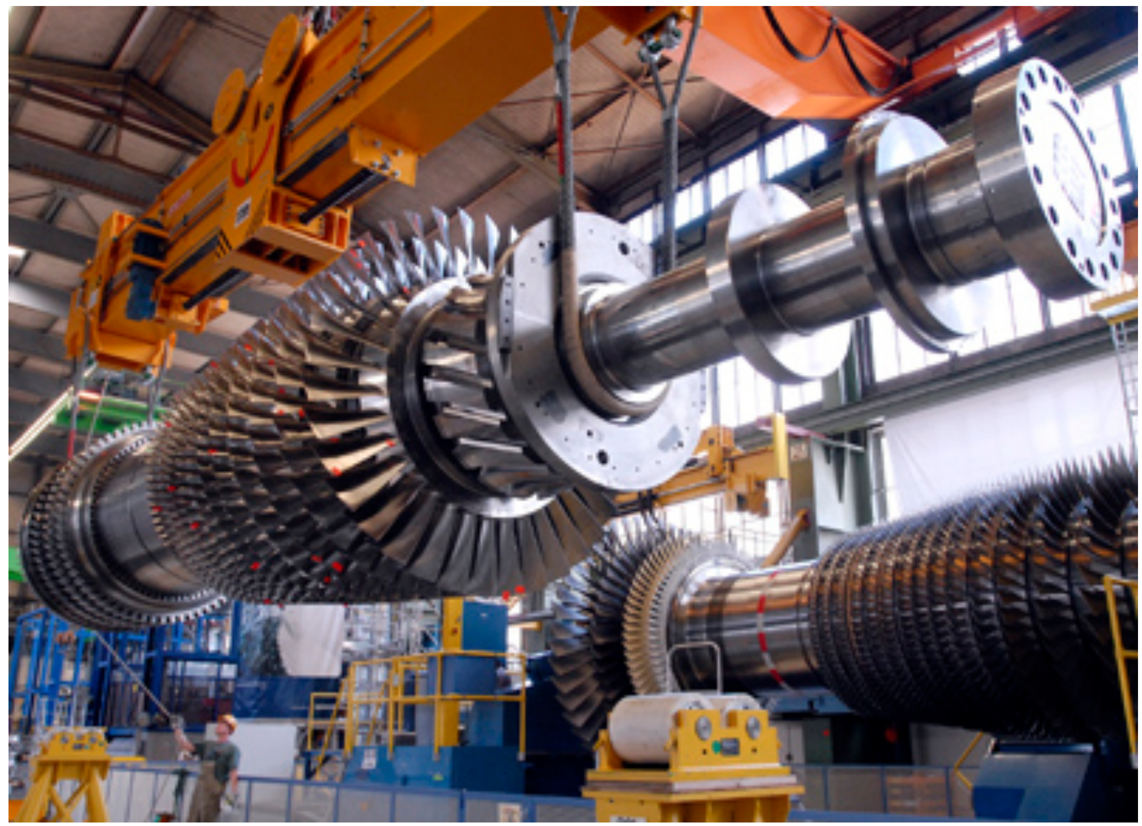






Most powerful internal combustion engine

- Wartsila-Sulzer RTA96-C is largest IC engine, but Space Shuttle Solid Rocket Boosters are most powerful (≈ 42 *million* horsepower (32 hp/lb); not shaft power but kinetic energy of exhaust stream)
- Most powerful shaft-power engine: Siemens SGT5-8000H stationary gas turbine (340 MW = 456,000 HP) (0.52 hp/lb) used for electrical power generation (natural gas fuel)



Smallest internal combustion engine

- Cox Tee Dee 010

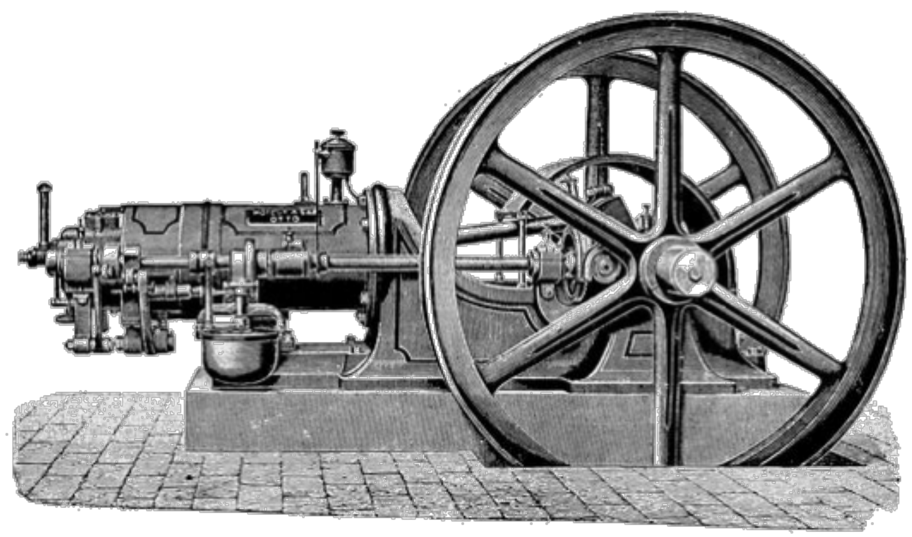
Application:	model airplanes
Weight:	0.49 oz.
Displacement:	0.00997 in^3 (0.163 cm^3)
RPM:	30,000
Power:	5 watts
Ignition:	Glow plug

- Typical fuel: 65% methanol, 15% nitromethane, 20% castor oil
- Good power/weight (0.22 hp/lb) but poor performance
  - Low efficiency (< 3%)
  - Emissions & noise unacceptable for many applications

History of automotive engines

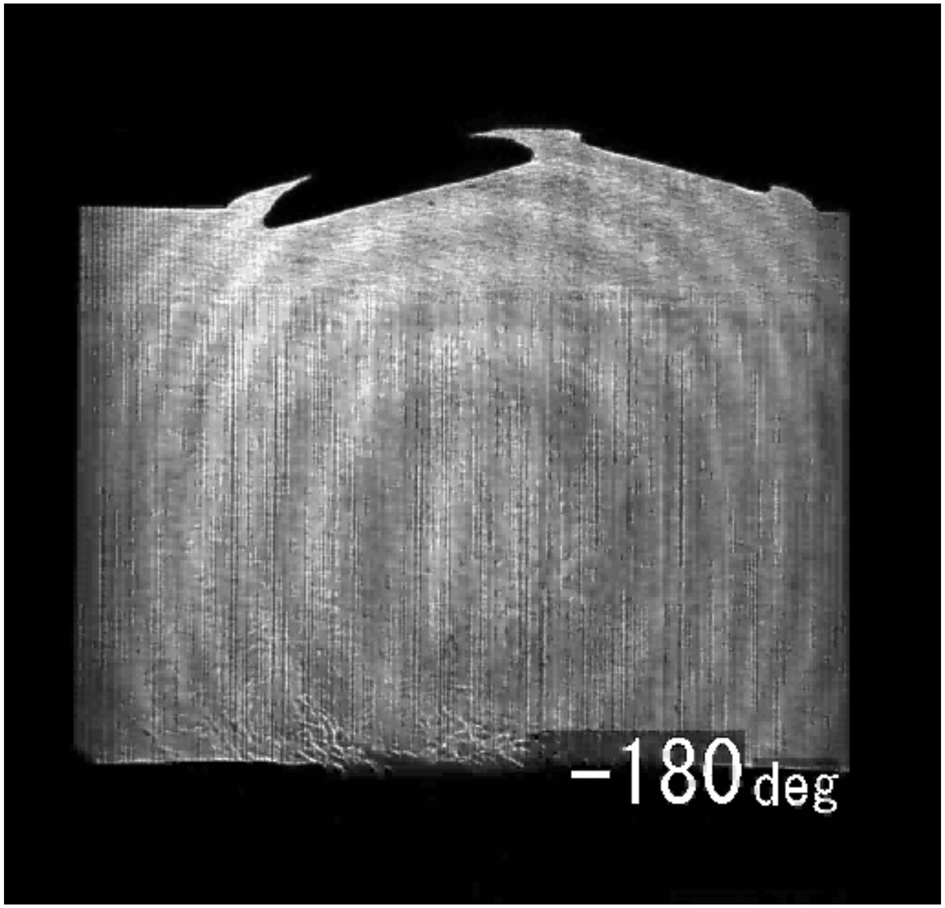
- 1859 - Oil discovered at Drake's Well, Titusville, Pennsylvania (20 barrels per day) - 40 year supply
- 1876 - Premixed-charge 4-stroke engine – Nikolaus Otto
  - 1st "practical" ICE
  - Overhead valves + crankshaft
  - 5.1 liter; 1300 lb; 160 RPM; 2 hp
  - Fuel: coal gas ($CO + H_2$)
  - Compression Ratio (CR) = 4 (knock limited), 14% efficiency (theory 38%)

$$\text{Efficiency} = \frac{\text{What you get}}{\text{What you pay for}} = \frac{\text{Work output}}{\text{Fuel energy input}}$$

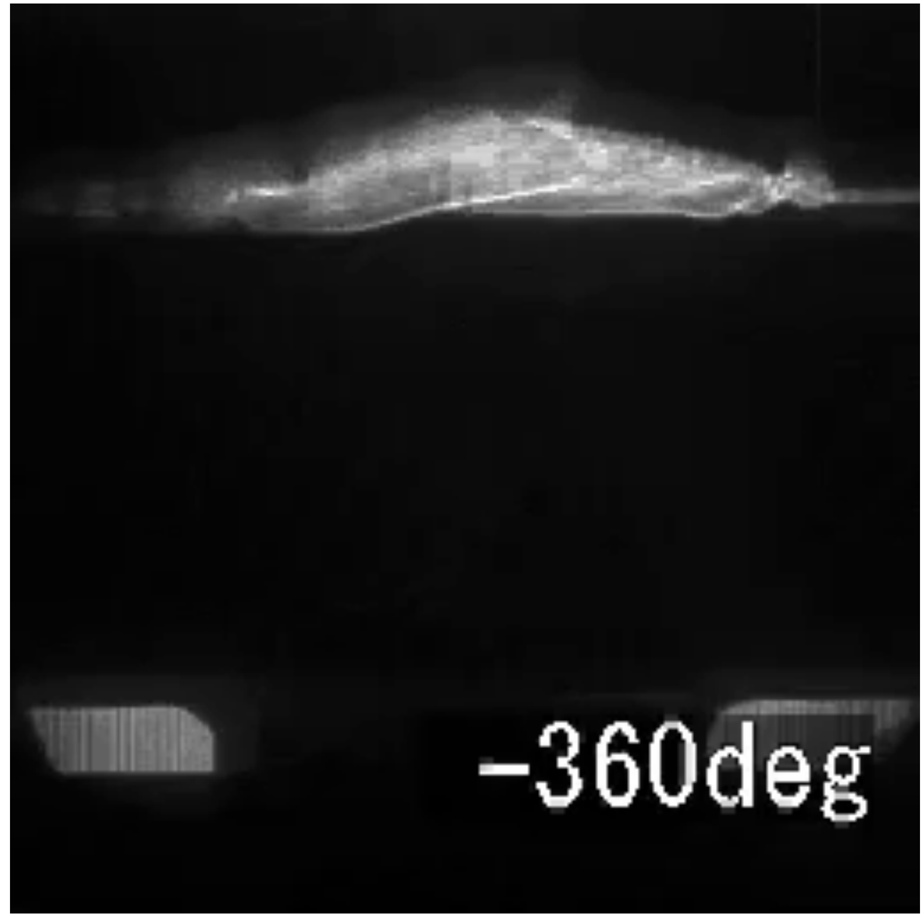


- Today CR = 9 (still knock limited), 30% efficiency (theory 55%)
- In 138 years, the main efficiency improvement is due to better fuel

Engine knock - movies



No knock

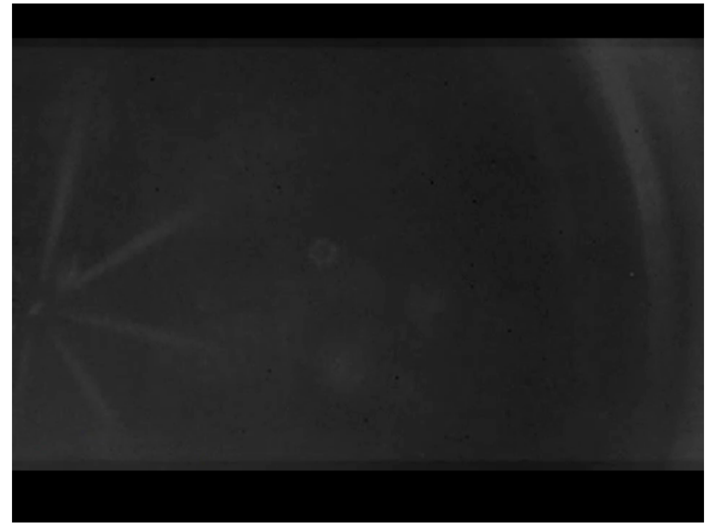


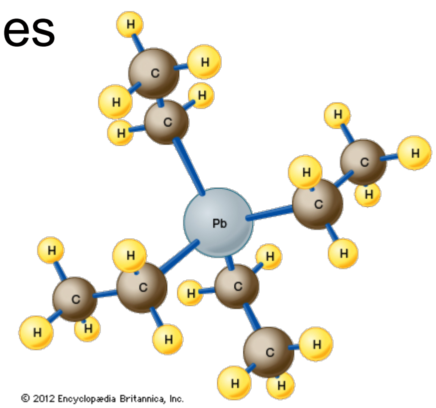
Knock

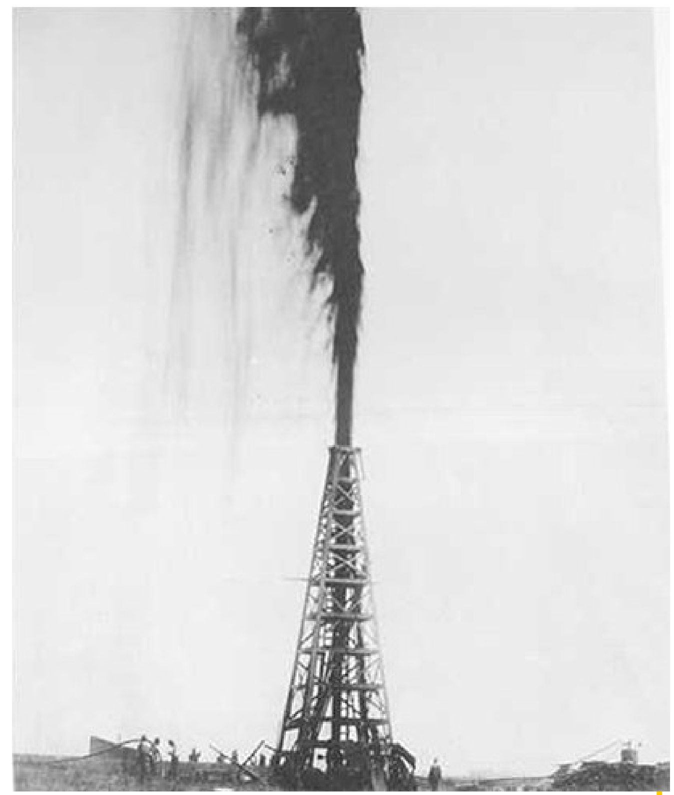
Videos courtesy Prof. Yuji Ikeda, Kobe University

History of automotive engines

- 1897 - Nonpremixed-charge (Diesel) engine - compress air only then inject fuel - higher efficiency due to
  - Higher CR (no knocking)
  - No throttling loss - use fuel/air ratio to control power
- 1901 - Spindletop Dome, east Texas - Lucas #1 gusher produces 100,000 barrels per day - ensures that "2nd Industrial Revolution" will be fueled by oil, not coal or wood - 40 year supply
- 1921 - Tetraethyl lead anti-knock additive discovered at General Motors
  - Enabled higher CR (thus more power, better efficiency) in Otto-type engines
  - "End of the line" for steam & electric vehicles







History of automotive engines

- 1938 – Oil discovered at Dammam, Saudi Arabia (40 year supply)
- 1952 - A. J. Haagen-Smit, Caltech

$$\underset{\text{(from exhaust)}}{NO + UHC} + O_2 + \text{sunlight} \rightarrow \underset{\text{(brown)}}{NO_2} + \underset{\text{(irritating)}}{O_3}$$

(UHC = unburned hydrocarbons)

- 1960s - Emissions regulations
  - Detroit wouldn't believe it
  - Initial stop-gap measures - lean mixture, exhaust gas recirculation (EGR), retard spark
  - Poor performance & fuel economy
- 1973 & 1979 - The energy crises due to Middle East turmoil
  - Detroit takes a bath, Asian and European imports increase

History of automotive engines

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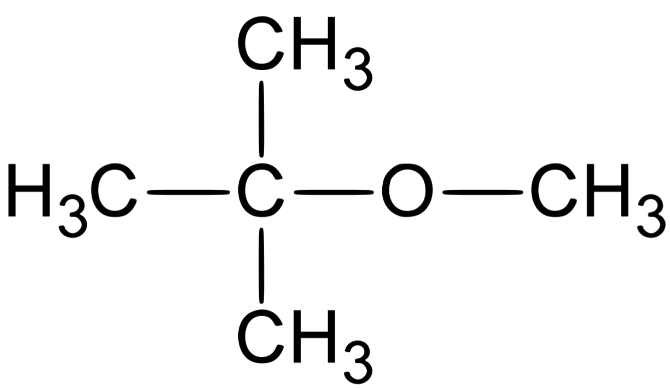
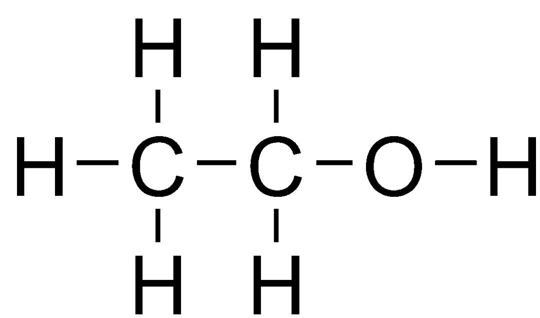
- 1975 - Catalytic converters, unleaded fuel
  - More "aromatics" (e.g., benzene) in gasoline - high octane but carcinogenic, soot-producing
- 1980s - Microcomputer control of engines
  - Tailor operation for best emissions, efficiency, ...
- 1990s - Reformulated gasoline (e.g., MTBE)
  - Reduced need for aromatics, cleaner (?)
  - ... but higher cost, lower miles per gallon
  - Then we found that MTBE pollutes groundwater!!!
  - Alternative "oxygenated" fuel additive - ethanol - very attractive to powerful senators from farm states in the USA



MTBE



Ethanol

History of automotive engines

- 2000s - hybrid vehicles
  - Use small gasoline engine operating at maximum power (most efficient way to operate) or turned off if not needed
  - Use generator/batteries/motors to make/store/use surplus power from gasoline engine
  - Plug-in hybrid: half-way between conventional hybrid and electric vehicle
  - 2 benefits to car manufacturers: win-win
    - » Consumers pay a premium for hybrids
    - » Helps to meet fleet-average standards for efficiency & emissions
  - Do fuel savings justify extra cost? Consumer Reports study: only 1 of 7 hybrids tested showed a cost benefit over a 5 year ownership if tax incentives were removed
    - » Dolly Parton: "It costs a lot of money to look this cheap"
    - » PDR: "You have to consume a lot of energy to save a little fuel"
- 2010 and beyond
  - Electric vehicles
  - Small turbocharged gasoline engines (e.g. Ford EcoBoost™)

Things you need to understand before ...

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…you invent the zero-emission, 100 mpg 1000 hp engine, revolutionize the automotive industry and shop for your retirement home on the French Riviera

- Room for improvement - factor of less than 2 in efficiency
  - Ideal Otto cycle engine with compression ratio = 9: 55%
  - Real engine: ≤ 30%
  - Differences because of
    - Throttling losses
    - Heat losses
    - Friction losses
    - Slow burning
    - Incomplete combustion is a very minor effect
- Majority of power is used to overcome air resistance - smaller, more aerodynamic vehicles beneficial

Things you need to understand before ...

- Room for improvement - infinite in pollutants
  - Pollutants are a non-equilibrium effect
    - » Burn: Fuel + O_2 + N_2 $\rightarrow$ H_2O + CO_2 + N_2 + CO + UHC + NO

      OK OK(?) OK Bad Bad Bad
    - » Expand: CO + UHC + NO "frozen" at high levels
    - » With slow expansion, no heat loss:

      CO + UHC + NO $\rightarrow$ H_2O + CO_2 + N_2

      ...but how to slow the expansion and eliminate heat loss?
  - Worst problems: cold start, transients, old or out-of-tune vehicles - 90% of pollution generated by 10% of vehicles

Things you need to understand before ...

- Room for improvement - very little in power
  - IC engines are air processors
    - » Fuel takes up little space
    - » Air flow = power
    - » Limitation on air flow due to
      - "Choked" flow past intake valves
      - Friction loss, mechanical strength - limits RPM
      - Slow burn
    - » How to increase air flow?
      - Larger engines
      - Faster-rotating engines
      - Turbocharge / supercharge

Alternative #1 - external combustion

- Examples: steam engine, Stirling cycle engine
  - Use any fuel as the heat source
  - Use any working fluid (high γ, e.g. helium, provides better efficiency)
- Heat transfer rate
  - Heat transfer per unit area (q/A) = k(dT/dx)
  - Turbulent mixture inside engine: $k \approx 100\ k_{no\ turbulence} \approx 2.5$ W/mK
  - $dT/dx \approx \Delta T/\Delta x \approx 1500K / 0.02$ m
  - $q/A \approx 187{,}500$ W/m^2
- Combustion: $q/A = \rho Y_f Q_R S_T$ = (10 kg/m^3) x 0.067 x (4.5 x 10^7 J/kg) x 2 m/s = 60,300,000 W/m^2 - 321x higher!
- CONCLUSION: HEAT TRANSFER IS TOO SLOW!!!
- That's why 10 large gas turbine engines ≈ large (1 gigawatt) coal-fueled electric power plant

k = gas thermal conductivity, T = temperature, x = distance,
ρ = density, Y_f = fuel mass fraction, Q_R = fuel heating value,
S_T = turbulent flame speed in engine

Alternative #2 - electric vehicles (EVs)

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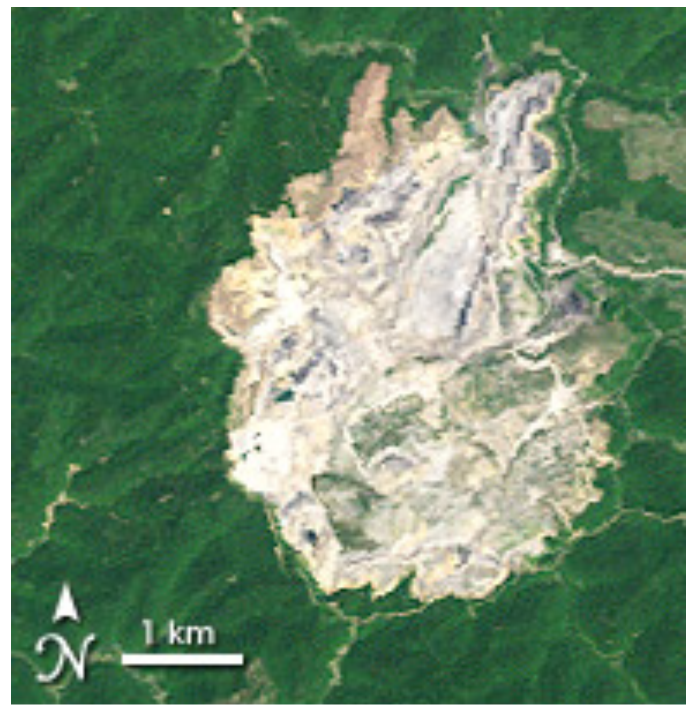
- Generate electricity in central power plant (efficiency $\eta \approx 35\%$), charge batteries, run electric motors ($\eta \approx 90\%$)
- Chevy Bolt Li-ion battery
  - 60 kWh (100% - 0% charge, diminishes battery life), 960 pounds = 5.0×10^5 J/kg (http://en.wikipedia.org/wiki/Chevrolet_Bolt)
  - Replacement list price $15,700
- Gasoline (and other hydrocarbons): 4.3×10^7 J/kg
- Even at 30% efficiency (gasoline) vs. 90% (batteries), gasoline has 29 times higher energy/weight than batteries!
- 1 gallon of gasoline ≈ 175 pounds of batteries for same energy delivered to the wheels
- Also – recharging rate: 7 KW (EV, home) or 85 KW (Tesla Supercharger station) vs. 5000 KW (gasoline pump)

“Zero emission” electric vehicles



Alternative #2 - electric vehicles (EVs)

- Other issues with electric vehicles
  - "Zero emissions" ??? - EVs export pollution
  - MPG_e = "equivalent" energy based only on electrical energy stored in the battery, not the energy required to generate that electricity
    - 100 MPG_e ≈ 35 MPG in terms of fuel burned (and CO_2 produced)
  - 33% of US electricity is by produced via coal at 35% efficiency – virtually no reduction in CO_2 emissions with EVs
  - Environmental cost of battery materials
  - Possible advantage: makes smaller, lighter, more streamlined cars acceptable to consumers
  - Plus side: cost of electricity (Joules/$) ≈ same as gasoline but ≈ 3x higher efficiency (fuel to shaft power), thus EVs have lower "fuel" cost
- Economics of batteries
  - Bulk Li-ion batteries cost ≈ $500/kW-hr (GM supplier: $145/kW-hr)
  - Lifetime 1000 charge/discharge cycles, thus $0.50/kW-hr
  - Cost of electricity ≈ $0.10/kW-hr
  - Battery cost is 5x greater than value of all electricity it can store over its entire lifetime – Tesla Powerwall™ makes no financial sense without subsidies

Alternative #2 - electric vehicles (EVs)

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- Tesla
  - Different strategy - performance car, not economy car – excels in acceleration, handling, …
  - “Zero Emission Vehicle” credits – worth ≈ $35,000 per vehicle (LA Times, 8/23/2013, page B4)
  - Cost ≥ $81,000 with 85 kW-hr battery (1200 lb) (5.6×10^5 J/kg)
  - “Free” electricity at their charging stations – what is value?

$$100{,}000 \text{ miles} \times \frac{\text{gallon}}{35 \text{ miles}} \times \frac{\$2.50}{\text{gallon}} = \$7{,}143$$

  - Option to replace battery after 8 years: $12,000 – more than wipes out free recharges

Alternative #3 - Hydrogen fuel cell

- NuCellSys HY-80 "Fuel cell engine" (power/wt = 0.19 hp/lb)
- 48% efficient (fuel to electricity)
- MUST use hydrogen (from where? H_2 is an energy carrier, not a fuel)
- Requires > $10,000 of platinum
- Does NOT include electric drive system
- Overall system: 0.13 hp/lb at 43% efficiency
- Conventional engine: ≈ 0.5 hp/lb at 30% efficiency
- Conclusion: fuel cell engines only marginally more efficient, much heavier & require hydrogen vs. gasoline
- Prediction: even if we had an unlimited free source of hydrogen and a perfect way of storing it on a vehicle, *we would still burn it, not use it in a fuel cell*

nucellsys.com

Hydrogen storage

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- Hydrogen is a great fuel
  - High energy density (1.2×10^8 J/kg, ≈ 3x hydrocarbons)
  - Faster reaction rates than hydrocarbons (≈ 10 - 100x at same T)
  - Excellent electrochemical properties in fuel cells
- But how to store it???
  - Cryogenic (very cold, -424˚F) liquid, low density (14x lower than water)
  - Compressed gas: weight of tank ≈ 15x greater than weight of fuel
  - Borohydride solutions
    - » $NaBH_4 + 2H_2O \rightarrow NaBO_2$ (Borax) + $3H_2$
    - » (mass solution)/(mass fuel) ≈ 9.25
  - Palladium - Pd/H = 164 by weight
  - Carbon nanotubes - many claims, few facts…
  - Long-chain hydrocarbon $(CH_2)_x$: (Mass C)/(mass H) = 6, plus C atoms add 94.1 kcal of energy release to 57.8 for H_2!
- MORAL: By far the best way to store hydrogen is to attach it to carbon atoms and make hydrocarbons, even if you're not going to use the carbon as fuel!

Alternative #4 - solar vehicles

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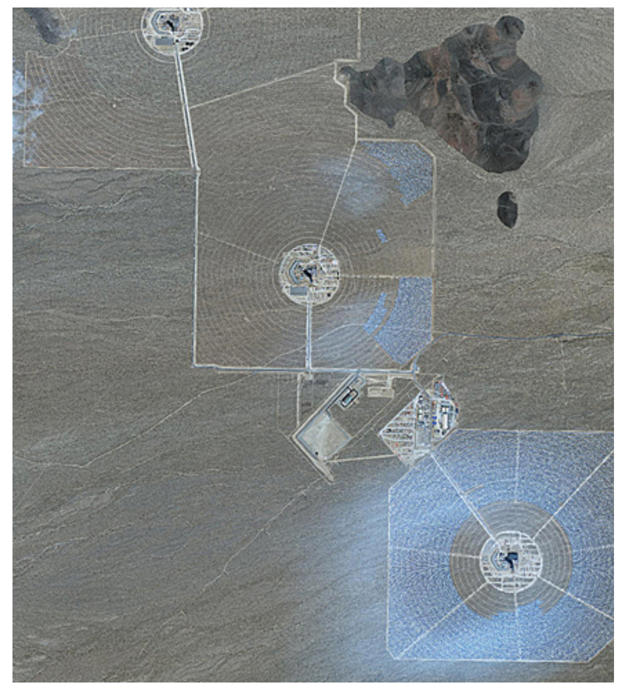
- Arizona, high noon, mid summer: solar flux ≈ 1000 W/m^2
- Gasoline engine, thermal power = (60 mi/hr / 30 mi/gal) x (6 lb/gal) x (kg / 2.2 lb) x (4.3 x 10^7 J/kg) x (hr / 3600 sec) = 65 kilowatts
- Need ≈ 65 m^2 collector ≈ 26 ft x 26 ft - lots of air drag, what about underpasses, nighttime, bad weather, northern/southern latitudes, etc.?

Do you want to drive one of these every day (but never at night?)

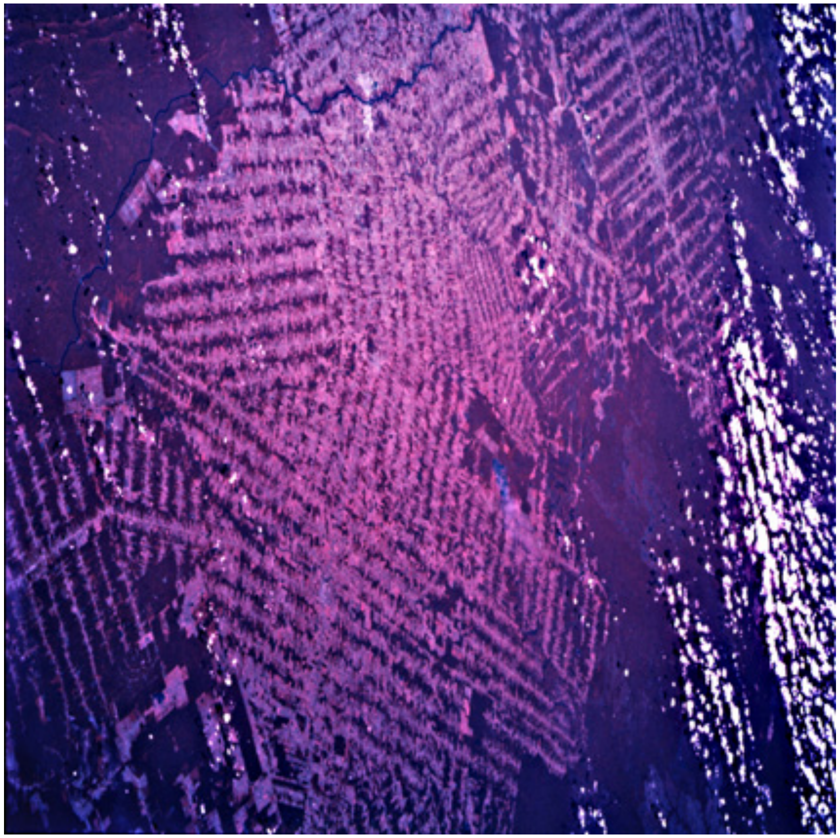
Alternative #4 - solar

- Ivanpah solar thermal electric generating station (California desert)
  - 3 towers, each 460 ft tall; land area 6 mi^2, 173,500 mirrors
  - 400 MW maximum power, 203 MW annual average in 2016 (typical coal or nuclear plant: 1,000 MW)
  - Annual natural gas usage (to keep boilers hot at night): 111 MW
  - Capital cost $2.2 billion = $18/watt vs. $1/watt for natural gas power plants, $3/watt for coal … and maintenance costs?
  - Impact on desert wildlife? (28,000 birds/yr?)
- Topaz solar photovoltaic, near Bakersfield: 144 MW avg., $17/watt



Alternative #5 - biofuels

- Essentially solar energy – "free" (?)
- Barely energy-positive; requires energy for planting, fertilizing, harvesting, fermenting, distilling
- Very land-inefficient compared to other forms of solar energy – life forms convert < 1% of sun's energy into combustible material
- Until 2011, 3 subsidies on US bio-ethanol:
  - 45¢/gal (≈ 67¢/gal gasoline) tax credit to refiners
  - 54¢/gal tariff on sugar-based ethanol imports
  - Requirement for 10% ethanol in gasoline
- Displaces other plants – not necessarily "carbon neutral"
- Uses other resources - arable land, water – that might otherwise be used to grow food or provide biodiversity (e.g. in tropical rain forests)



Alternative #6 - nuclear

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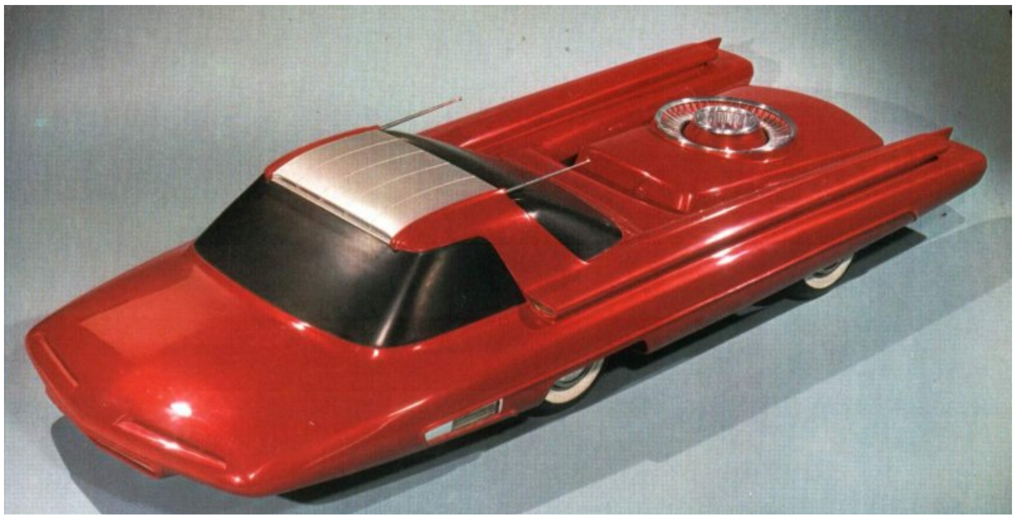
- Who are we kidding ???
- High energy density though
  - U_{235} fission: 8.2 x 10^{13} J/kg ≈ 2 million x hydrocarbons!
  - Radioactive decay much less (2.0 x 10^{9} J/kg for Pu-238), but still much higher than hydrocarbons



Ford Nucleon concept car (1958)

Alternative #7 – common sense

- http://www.edison2.com
- Won X-prize competition for 4-passenger vehicles (110 MPG)
- Low weight (830 lb), aerodynamic, very low rolling resistance
- Engine: 1 cylinder, 40 hp, 250 cc, turbocharged ICE
- Ethanol fuel (high octane, allows high CR thus high efficiency)
- Rear engine placement reduces air drag due to radiator
- Beat electric vehicles despite unfair advantage in US EPA MPG equivalency: 33.7 kW-hr electrical energy = 1 gal, same as raw energy content of gasoline – *doesn't account for fuel burned to create electrical energy!*

Conclusion - alternatives to IC engines

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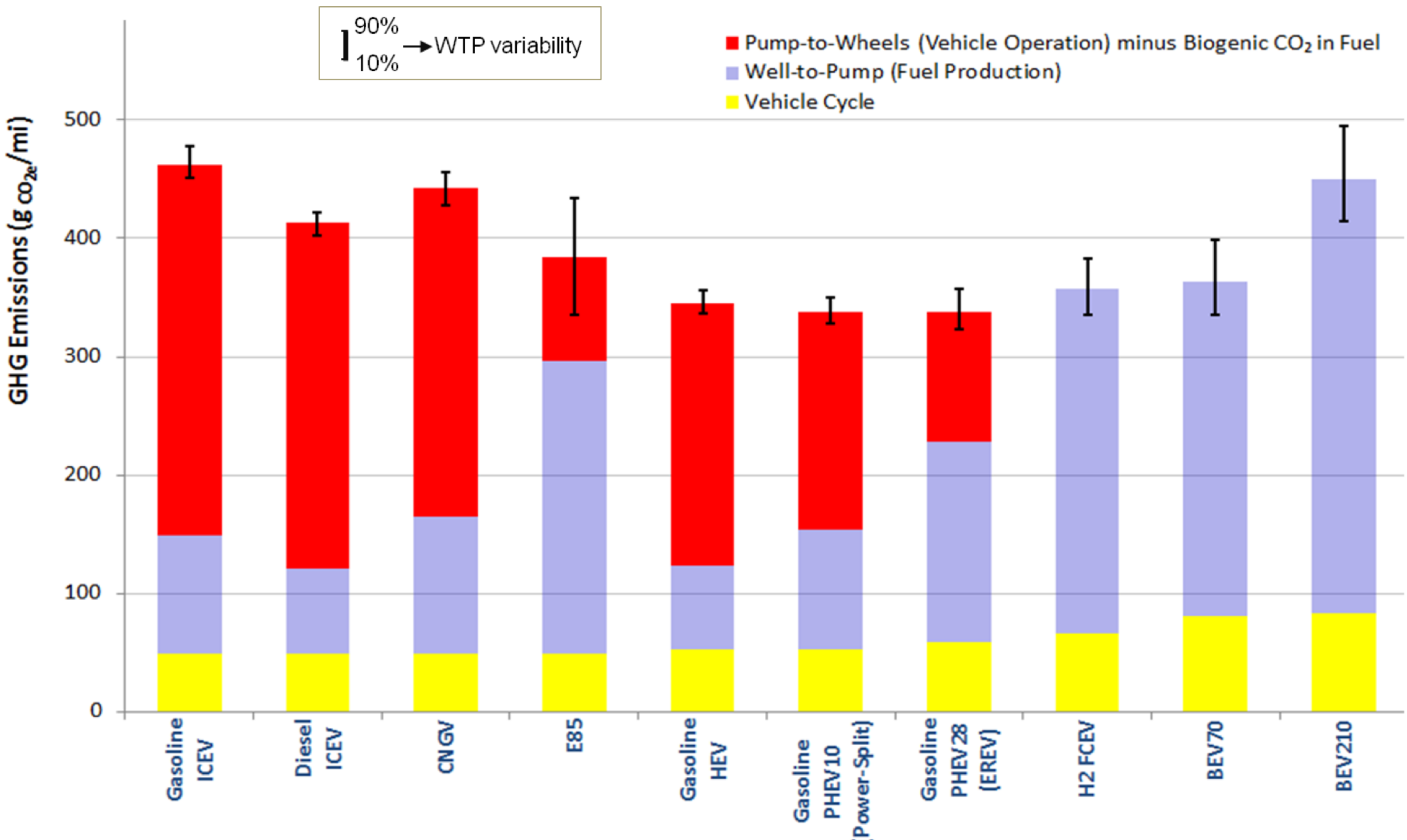
- Total "cradle to grave" CO_2 emissions ≈ same for all propulsion methods and energy sources!



http://www.hydrogen.energy.gov/pdfs/14006_cradle_to_grave_analysis.pdf

Summary of advantages of ICEs

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- Moral - hard to beat liquid-fueled internal combustion engines for
  - Power/weight & power/volume of engine
  - Energy/weight (4.3×10^7 J/kg) & energy/volume of liquid hydrocarbon fuel
  - Distribution & handling convenience of liquids
  - Relative safety of hydrocarbons compared to hydrogen or nuclear energy
  - Cost of materials (steel & aluminum)

Practical alternatives…

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- Conservation!
- Combined cycles
  - Use hot exhaust from ICE to heat water for conventional steam cycle
  - Can achieve > 60% efficiency
  - Not practical for vehicles - too much added volume & weight
- Natural gas (NG) – mostly methane (CH_4)
  - 4x cheaper than electricity, 2x cheaper than gasoline or diesel for same energy
  - Somewhat cleaner than gasoline or diesel, but no environmental silver bullet
  - Low energy storage density - 4x lower than gasoline or diesel
  - Lowest CO_2 emissions of any fossil fuel source
  - Problem: greenhouse effect of unburned NG (from production wells, filling stations, etc.) ≈ 8x that of burned NG

Practical alternatives… discussion points

- Fischer-Tropsch fuels - liquid hydrocarbons from coal or natural gas
  - Coal or NG + O_2 → CO + H_2 → liquid fuel
  - Competitive with $75/barrel oil
  - Cleaner than gasoline or diesel
  - … but using coal increases greenhouse gases!
    Coal : oil : natural gas = 2 : 1.5 : 1
  - What about using biomass (e.g. agricultural waste) instead of coal or natural gas as "energy feedstock"
- But really, there is no way to decide what the next step is until it is decided whether there will be a tax on CO_2 (and maybe other greenhouse gas) emissions
- Personal opinion: most important problems are (in order of priority)
  - Global warming
  - Energy independence
  - Environment

Conclusions

- IC engines are the worst form of vehicle propulsion, except for all the other forms
- Oil costs too much, but it's still very cheap
- We're 40 years away from running out of oil, and have been for the past 150 years
- There is no constituency for holistic, cradle-to-grave view of energy production with least total environmental impact