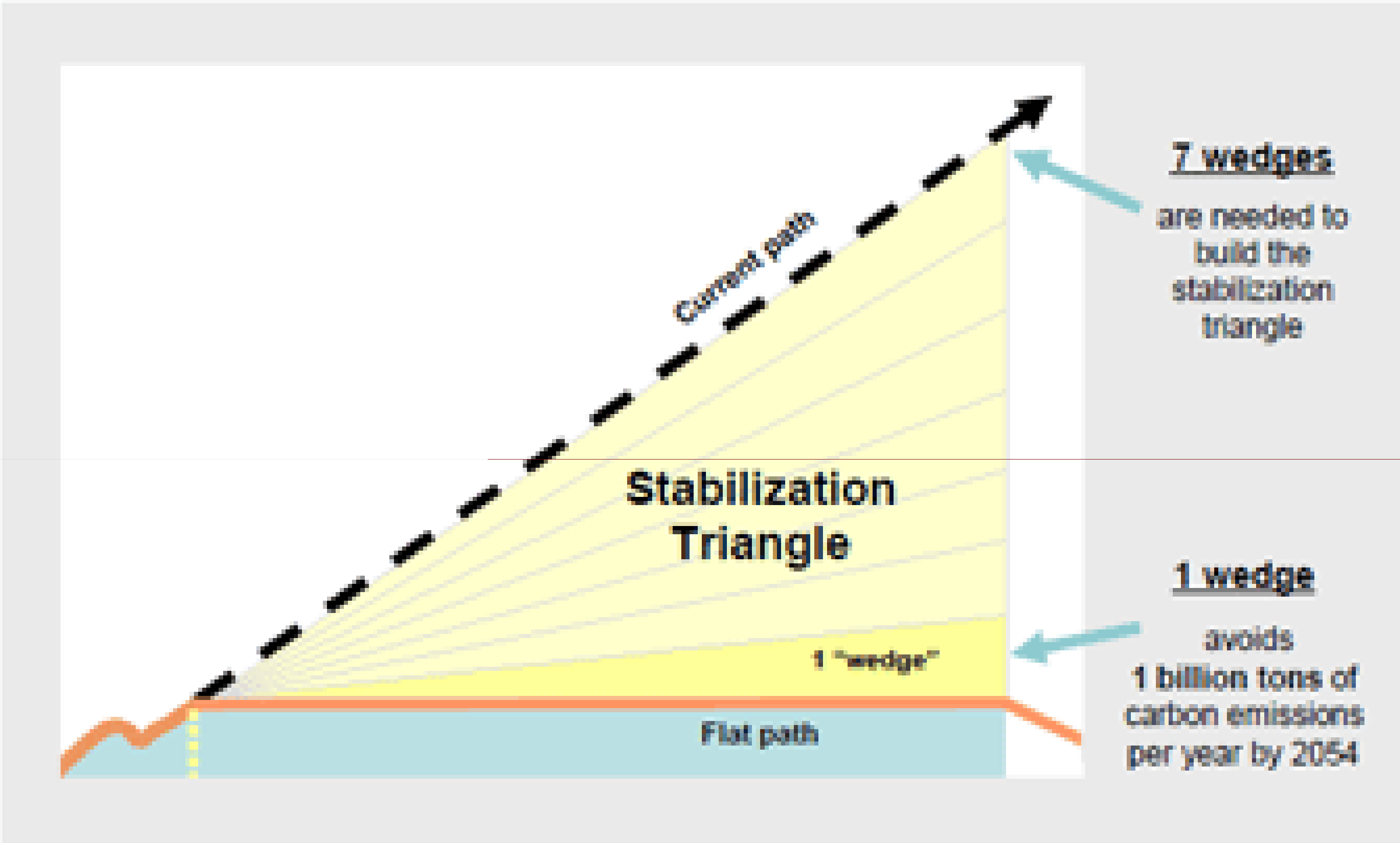
Why Discuss Fossil Fuels in Sustainable Energy?

- Is improving efficiency to reduce fossil fuel use by 1 TW the same as adding 1 TW of renewable energy generation?
  - In what ways is it the same? How is it different?
  - If cost of efficiency and cost of renewable were the same, which would you prefer? Why?
  - Which approach do you think is cheaper?
- The importance of SCALE: $6,000B/yr
  - Small percent changes are HUGE
  - Small percent investment in R&D is HUGE

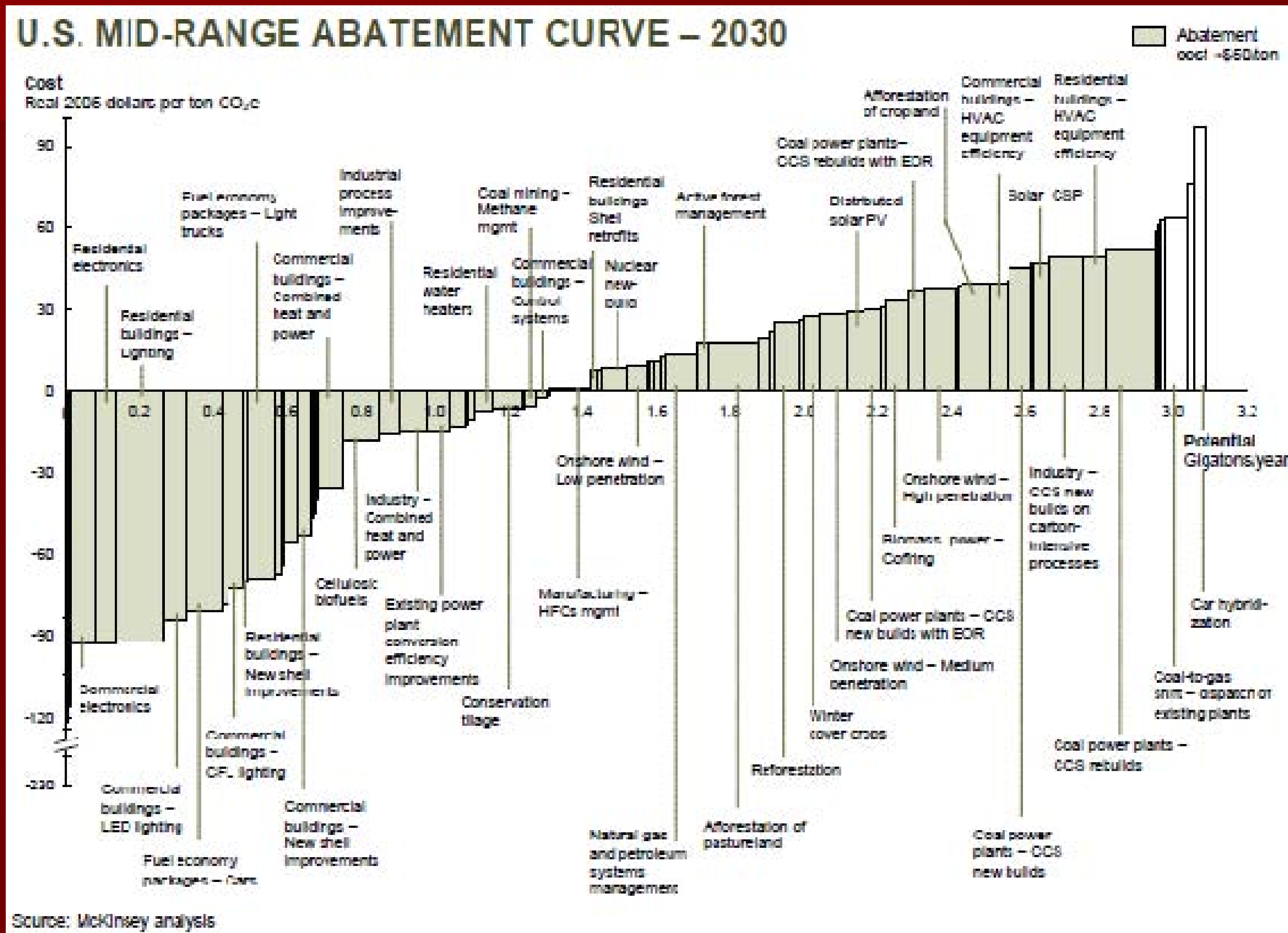
Wedge View of CO2 problem



Need 7 approaches, each providing a wedge. Many of the inexpensive options involve improving efficiency of fossil fuel utilization.

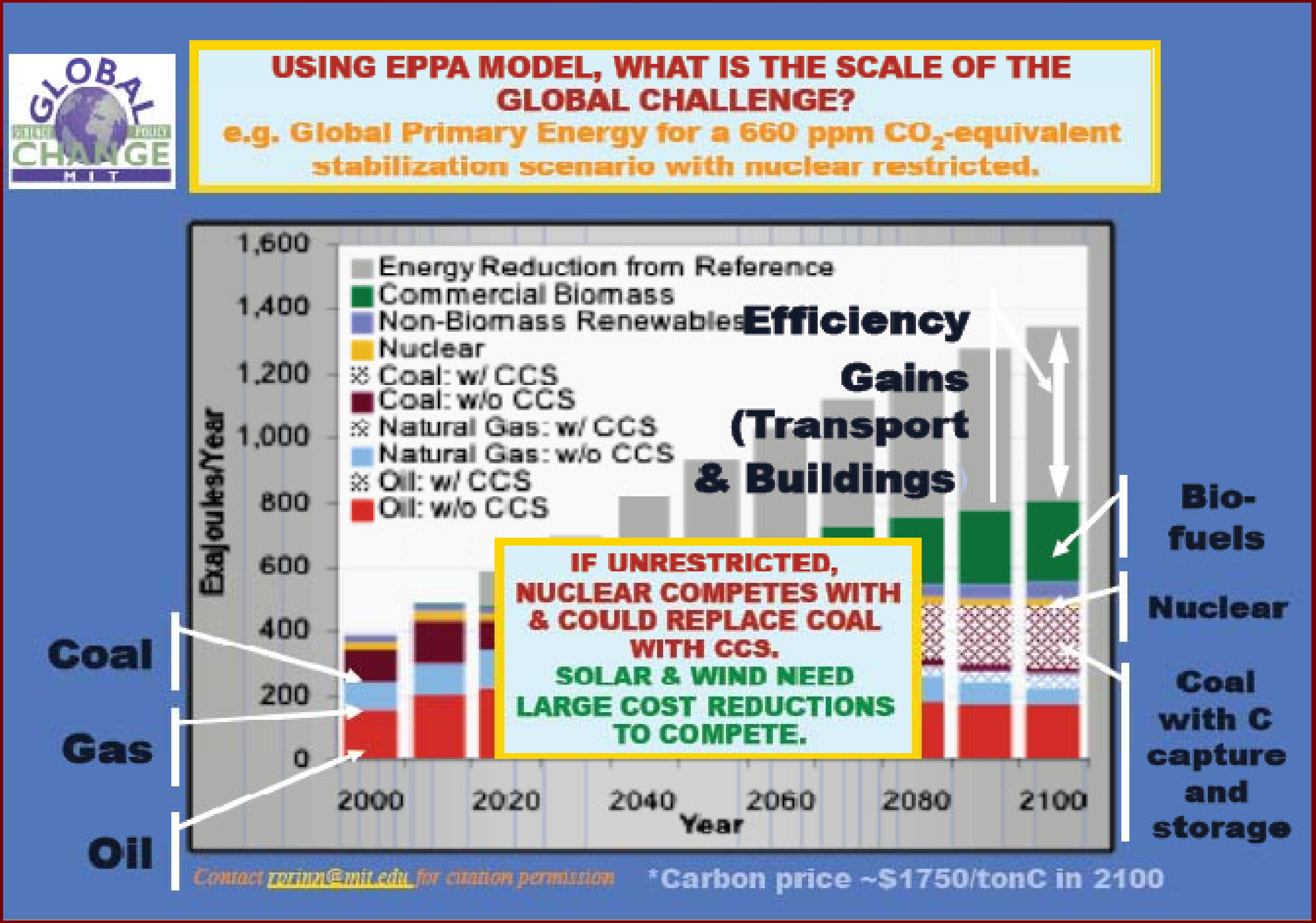
Graph by Carbon Mitigations Initiative, Princeton University.

The McKinsey Curve



Estimating $/ton of CO2 emissions avoided

One Proposal to stabilize CO2: Efficiency+Biofuel+CO2 CCS



Courtesy of Ronald Prinn. Used with permission.

Fossil Fuels III:
Liquid Fuels for Transportation

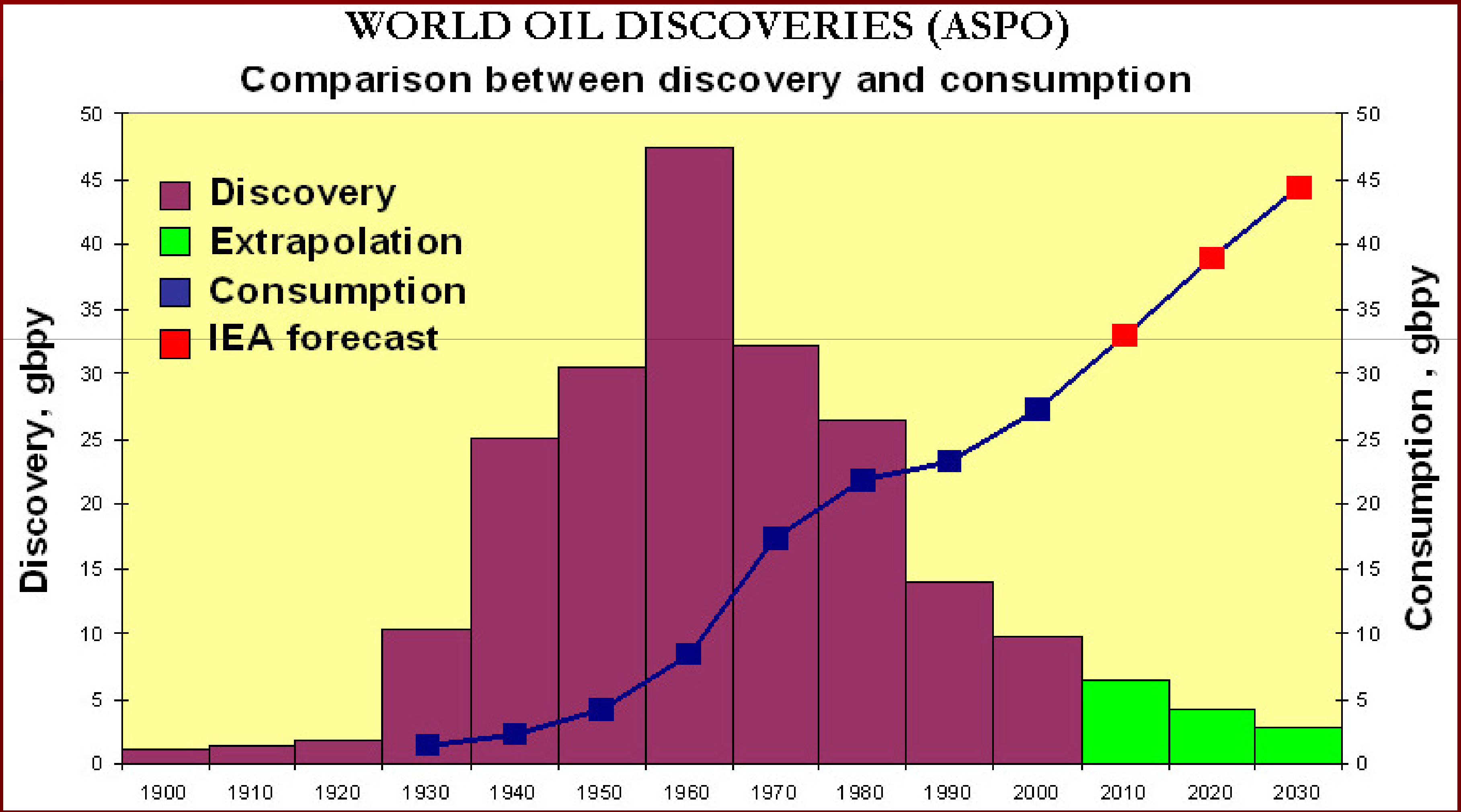
~30% of fossil fuel use
>50% of energy economics

Diesel, Gasoline, Jet Fuel
and the vehicles that burn them

Liquid Fuels Basics

- Almost 100% of transportation runs on liquid fuels (mostly petroleum)
  - And most petroleum is used for transportation
  - Well-established technology: reliable, convenient
- No technology in sight to replace liquid fuels for air transportation.
- Cars, trucks, trains: several future options
  - More efficient internal combustion engines
    - Fuel cells are another type of ‘engine’
  - Alternative liquid fuels
  - Gaseous fuels (natural gas, H2)
    - Need to generate the H2 (from natural gas?)
  - Electric (overhead wires or batteries)
    - Need to generate the electricity (from coal?)

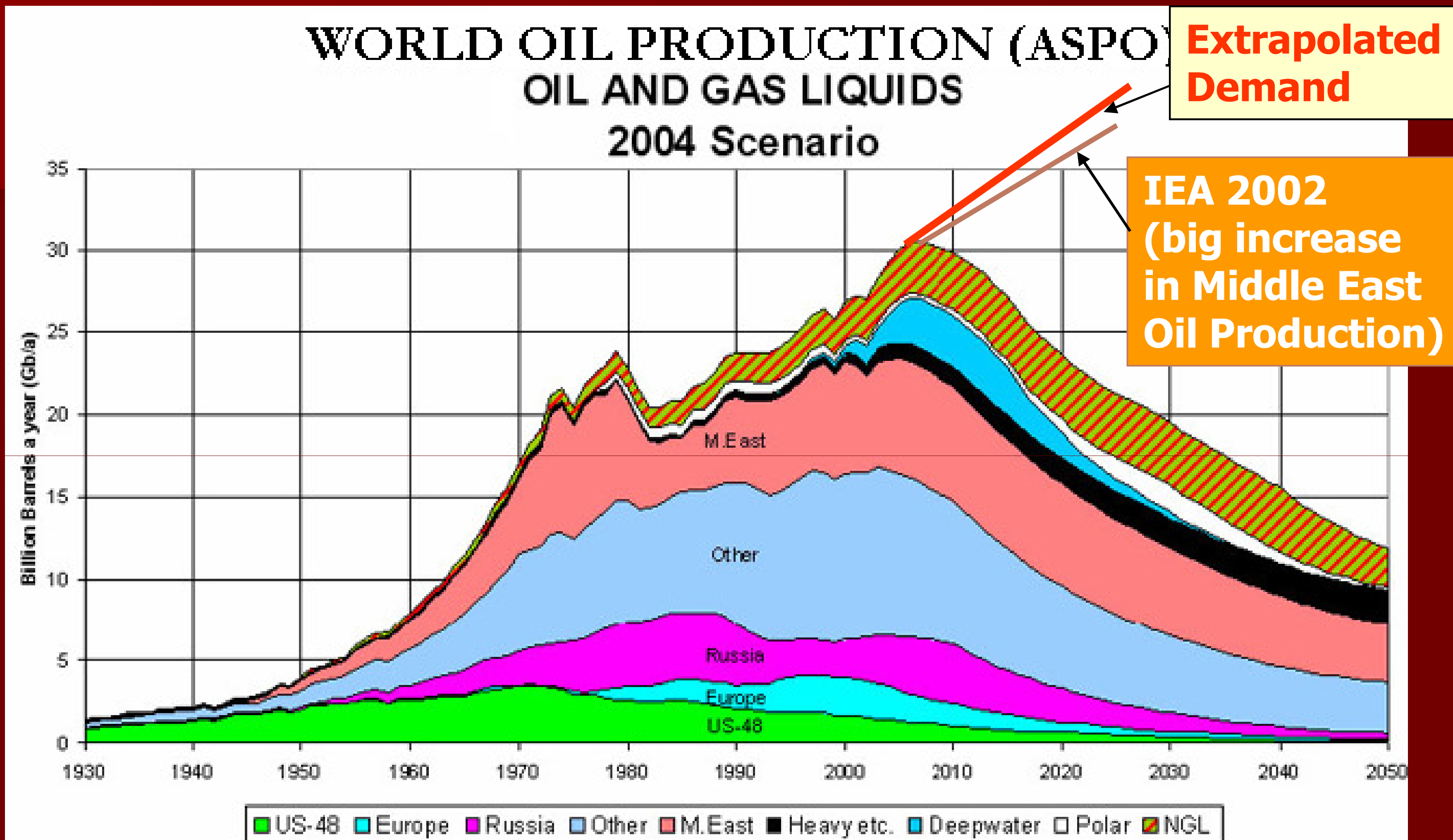
Liquid Fuel may run short: Since 1990, Discovering Less Oil than we are Burning



This image from: http://www.usnews.com/usnews/news/graphics/ace060315.pdf

Graph from Fournier, Donald F., and Eileen T. Westervelt. "Energy Trends and their Implications for U.S. Army Installations." U.S. Army Corps of Engineers (September 2005): ERDC/CERL TR-05-21.

Liquid Fuel Market Changing Dramatically



"…these are considered pessimistic projections. Others predict far higher production for the future… The optimists premise their estimates for the future entirely on production from the Middle East and Central Asia."

\- U.S. Army Corps of Engineers

Graph from Fournier, Donald F., and Eileen T. Westervelt. "Energy Trends and their Implications for U.S. Army Installations." U.S. Army Corps of Engineers (September 2005): ERDC/CERL TR-05-21.

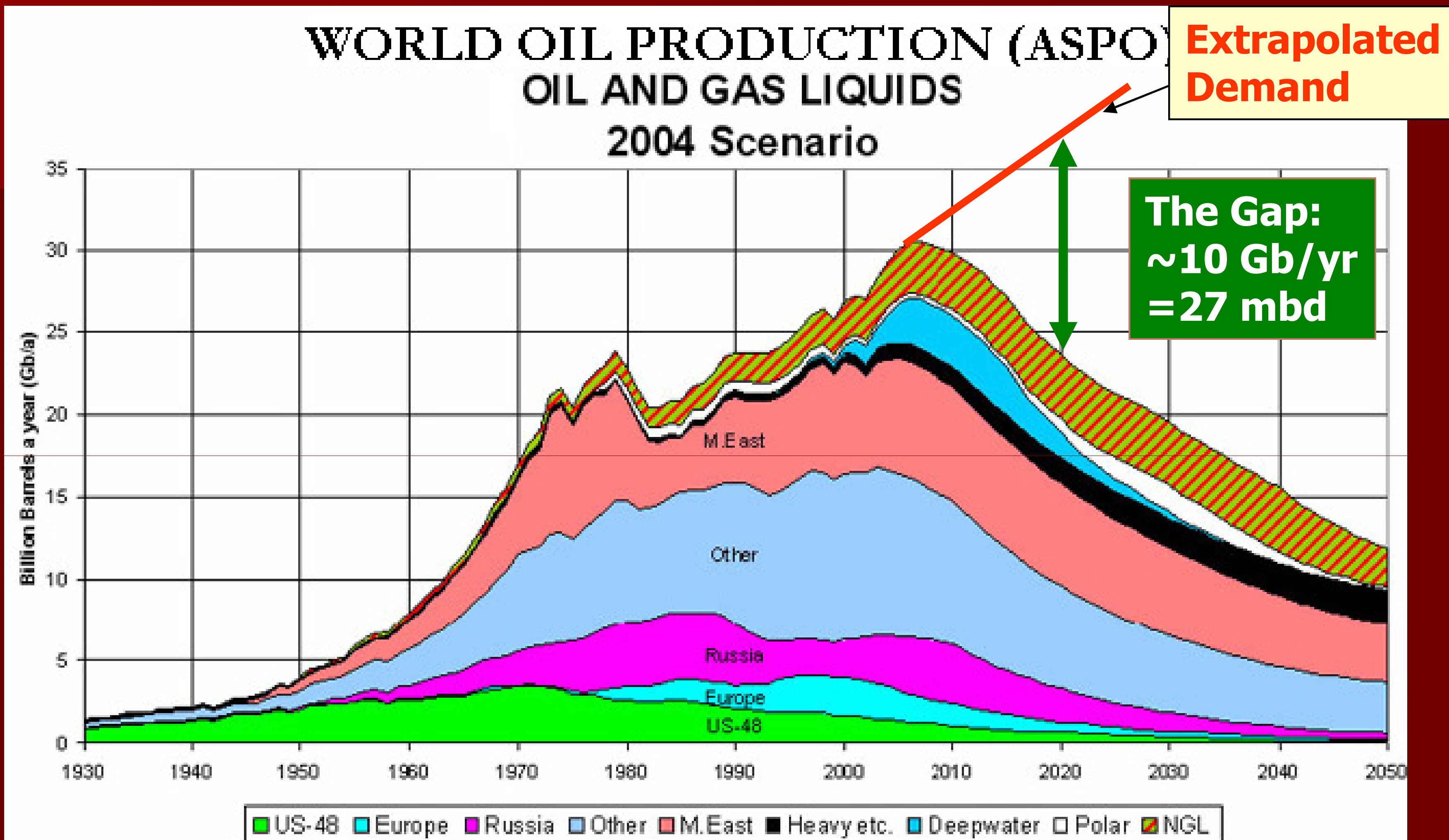
Experience with Oil Projections

- Historically, Nothing is ***Smooth***!
  - i.e. the smooth projections are Nonsense
  - Wars, economic cycles, natural disasters
  - Political changes (positive & negative)
  - Technology changes
- Fuel demand is not very elastic
  - prices can climb and fall very quickly
- High prices will inspire production
  - Big increase in Middle East production
  - Increases in all sorts of alternatives as well
  - Lag times of ~5 years in production increases
  - High price can drive world economy into recession.

Price is almost *impossible* to predict.
Fuel taxes, subsidies & regulations even worse.

Graph of crude oil prices from 1947-2009 removed due to copyright restrictions.

Big Transportation Fuels Supply Gap



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What could fill gap between transport liquid fuel demand & oil production?

- Venezuelan tar ("extra heavy oil")
- Unexpected oil discoveries or production rates
- Improved petroleum recovery rates
- Gas-to-Liquids
- Faster than expected development of tar sands
- Improved transport system efficiency
- Coal-to-Liquids (methanol?)
- Shale oil
- Gaseous fuels for transportation (CNG, H2)
- Conventional biofuels (from sugars, oils)
- Fuels from other biomass (e.g. cellulosic)
- Electricity

One way out: don't use liquid fuels at all!

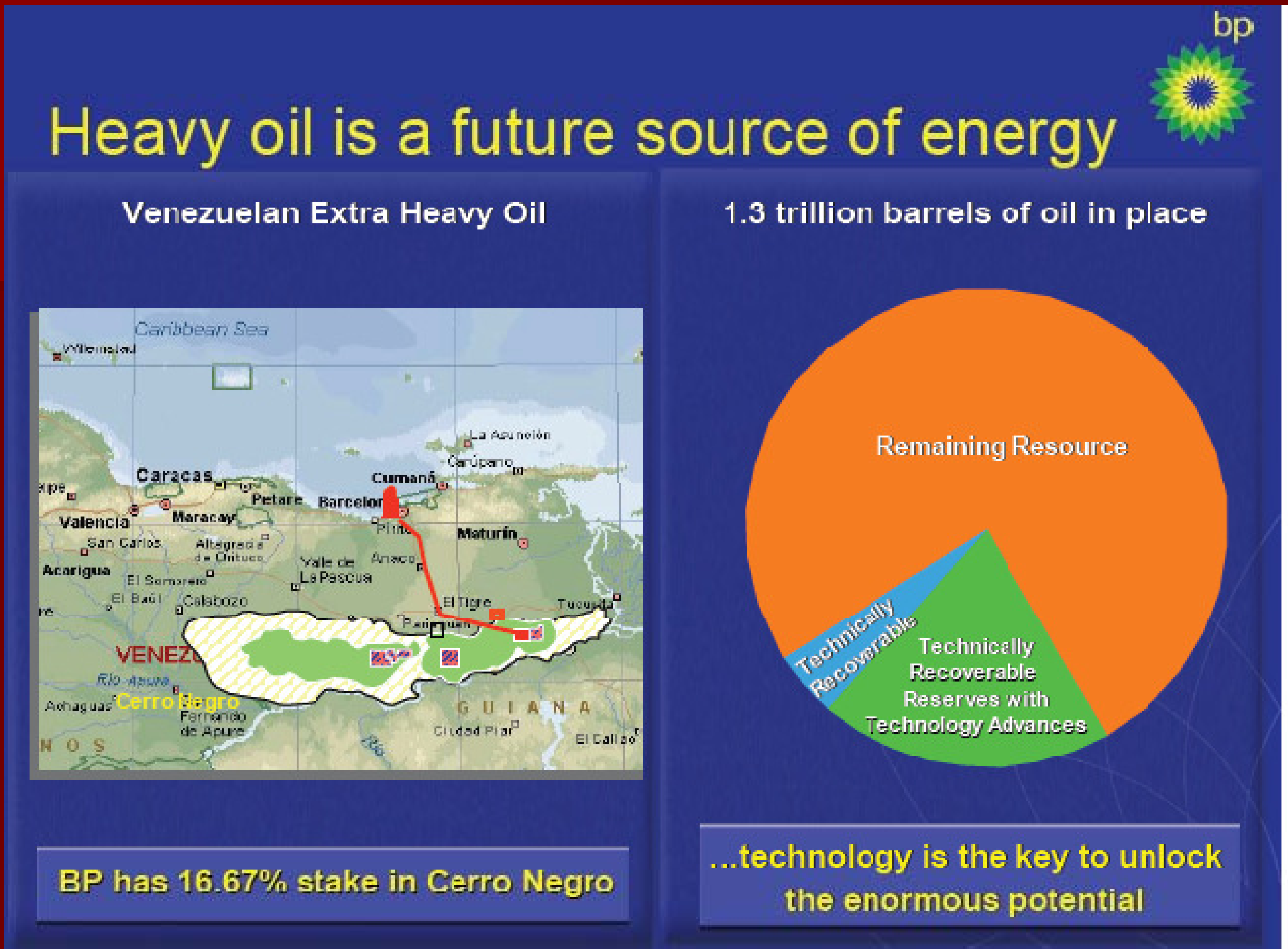
Photo by IFCAR on Wikimedia Commons.

Chevrolet Volt

"Electric cars are nearly ready…"

Boston Globe – July 22, 2007

Note electricity probably will come from burngin coal; might solve oil shortage but not greenhouse gas problem.



Slide from S. Koonin talk at MIT Sept. 2005

Or will the gap be filled with biofuels?

Photos by Kables on Flickr and Nyttend on Wikimedia Commons.

Will need to convert cellulose too, to significantly close the gap. Conventional biofuel production uses a lot of natural gas.

Hydrogen instead of batteries? Fuel cells instead of heat engines?

Photo by Anika Malone on Flickr.

Honda FCX Prototype

H_2 could be made from natural gas (w/ CO2 emissions): Price? Distribution? Range of vehicle?

Gaseous Fuels: CNG is simple and abundant

Photo by Christian Giersing on Wikimedia Commons.

Volvo B10BLE

Hard to achieve acceptable range with gaseous fuels.

Natural Gas supplies are limited in US, EU, China. Maybe better to use it for heating, chemicals, electricity?

LIQUID FUEL WOULD BE MUCH BETTER!

Options for making liquid fuels

- Gas-to-Syngas-to-Liquids
  - Commercial: Sumatra, Qatar
  - Requires cheap gas, has to compete with LNG
- Coal-to-SynGas-to-Liquids
  - Commercial: South Africa, now China.
- Coal Liquefaction
  - Commercialized by Germany during war.
- Biofuels (Ethanol, treated vegetable oil)
  - Commercial: Brazil, USA, EU.
- Oil Shale pyrolysis
  - Has been commercial in many countries.
- Melt tar out of Tar Sands, then upgrade.
  - Commercial: Canada

Need to Look at Whole Picture

- All synfuels processes are complicated
  - Each step adds expense & reduces efficiency.
  - Most processes greatly *increase* CO_2 emissions!
  - Modularize to deal with complexity, but…
- What do we really want?
  - Gasoline? Jet fuel? Diesel? Fuels for new engines?
  - Electricity?
- Need Integrated View
  - co-optimize "independent" modules.
  - Integrated View should drive R&D focus.
  - Policy: CO_2 sequestration? Other externalities?

Making Liquid Fuels from Nonliquids

- Converting Tar (or Shale) to ordinary fuels
  - **2 mbd operational or under construction**
- Gas-to-Liquids (Fischer-Tropsch diesel)
  - **0.4 mbd operational or under construction.**
- Coal-to-Liquids (F-T diesel, F-T gasoline, or methanol)
  - **0.15 mbd in South Africa**
  - **Planned construction of ~1 mbd in China**

- Common features:
  - **Huge capital investments in the conversion units**
  - **Long lead times (~5 years).**
  - **Capex dominated: once you build a unit, never turn it off.**
  - **Conversion losses imply extremely large CO_2 emissions**
  - **Capturing & sequestering CO_2 reduces efficiency, adds to capex.**

Research Issues: Chemistry

- Alternative chemical routes to liquid fuels?
  - CH_4 + air,heat → something condensable?
    - avoid two-step process. Air instead of O_2?
    - Need separation methods that work at reactor T
  - Coal + H_2 → valuable liquids
    - avoid syngas step and air separation
    - Need better quality liquid products than made with existing coal liquefaction processes.
- Catalysts that more selectively remove N from shale oil, minimize H_2 consumption.
- Reactions (and separations) that work at T's that allow better heat integration.

Properties of a successful new fuel

- Liquid, high energy density. C/H/O only.
- Volatility of gasoline or light diesel.
- If polar, must be biodegradable to avoid groundwater contamination.
- If soluble in gasoline/diesel, must be some *special advantage* in keeping it separate.
  - Much Better Engine or Emissions Performance

Alternative Liquid Fuels: The $64,000 Question

- Currently most new liquid fuels are diluted into petroleum-derived gasoline or diesel
  - – Minimizes engine perturbation
  - – No need for new distribution infrastructure
  - – New fuel valued about same as oil. (Risk: oil price can fall below cost to produce the new fuel).
- In the future, will gas stations stock some new 3rd fuel in addition gasoline and diesel?
  - – Would open up many new engine possibilities.
  - – New fuel might command higher price than oil.
    - But only if it provides a big advantage!

Some possible new fuels

- Oil insoluble biodegradable fuels
  - Polyols, certain other polyoxygenates
  - Most likely from biomass
  - Relatively little is know about this option.
- Alcohols, other oil-soluble oxygenates
  - Methanol, ethanol (GTL, CTL, or bio)
    - Unusual vaporization & energy density
  - Heavier oil-soluble oxygenates (from biomass)
    - Similar to oil, any advantage to keep separate??

What is needed for a 3rd Fuel to become established?

- All stakeholders must consent
  - Vehicle makers
  - Fuel makers/distributors
  - Political leaders
  - Consumers
- Mutual consent must persist for many years
- What could prompt such remarkably broad and long-lived consensus?

What could prompt long-lived consensus on a new fuel?

- All the stakeholders should derive some benefit from the new fuel's introduction.
  - There must be a significant advantage to the 3rd fuel.
  - How to share the benefit amongst all shareholders?
- Most challenging for fuels which mix into oil.
  - ***Must be a clear advantage in keeping the new fuel separate.***

Boring version of Dual Fuel:

Fuels are not miscible.

Use Fuel B only if Fuel A is not available

(backup for unreliable distribution system)

Photo of a diesel/CNG bus in New York City removed due to copyright restrictions.

Dual Fuel Compressed Natural Gas/Diesel

(since CNG is not available everywhere)

Flexible Fuel Vehicles:

Again, vehicle compensating for unreliable fuel distribution system

Photo of an E85 Chevrolet Avalanche at the Chicago Auto Show, February 8, 2006 removed due to copyright restrictions.

No compelling reason to keep E85 separate from the main gasoline stream

Interesting versions of Dual-Fuel:

Performance Advantage from using both fuels

Adjust fuel mix to optimize performance.

Photo of ArvinMeritor test vehicle and Clean Air Power dual-fuel truck removed due to copyright restrictions.

ArvindMeritor bus
running diesel/H_2 mix

Clean Air Power truck
running CNG/diesel mix

Many other promising dual fuel concepts, e.g. for SI, HCCI…
Are benefits sufficient to drive wide introduction of a 3rd fuel?

Third "fuel" could be Electricity: e.g. Plug-In Hybrids

Photo of plug-in hybrid cars removed due to copyright restrictions.

A pair of plug-in hybrid electric vehicles are tested at Argonne's Transportation Technology R&D Center

Approaching a fork in the road…

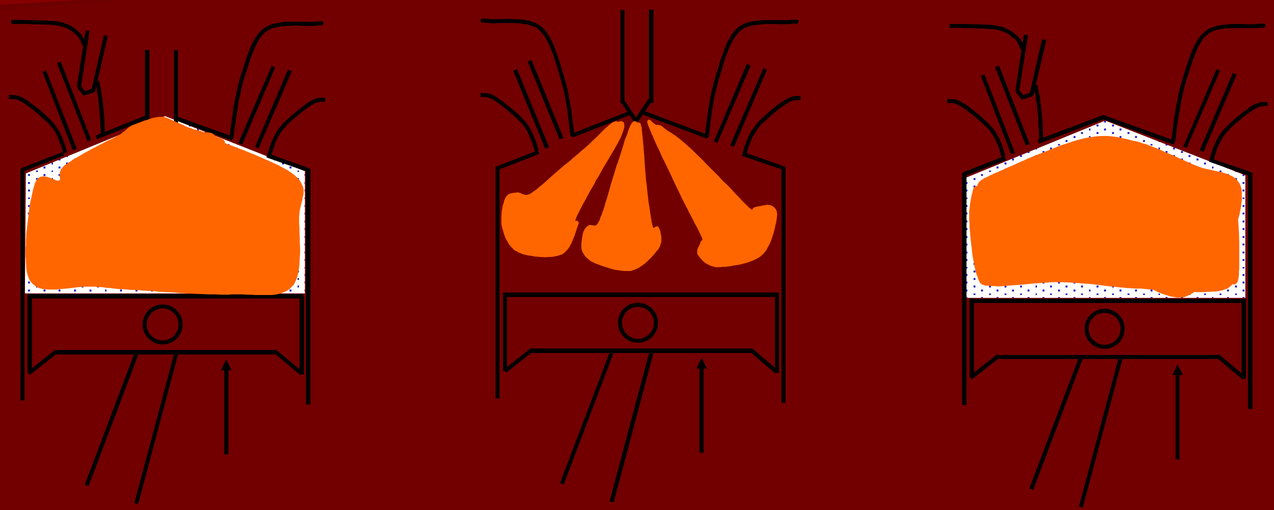
- Huge change in liquid fuel mix is coming:
  - There is not enough oil! It is expensive!
  - Current system is not environmentally responsible.
  - No one has energy security.
- Difficult to predict which fuels will fill gap
  - depends on policy decisions (climate, security, economics)
- Window of opportunity to add a 3rd fuel at the pump
  - Electricity (e.g. plug-in hybrid)?. Gases?? Polar liquids??
  - A third oil-soluble fuel could become widely available, if…
    - new vehicle technology can deliver big advantages by keeping the third fuel distinct.
    - The benefits of the new fuel are perceived and shared amongst the many stakeholders.

A taste of R&D

- *Mechanical Engineering*, Nov. 2009:
  - "Blending Diesel Fuel with Gasoline can improve diesel engine fuel efficiency by an average of 20%...the best tests achieved 53% thermal efficiency"
  - This engine invented by Rolf Reitz was a dual-fuel variant on HCCI

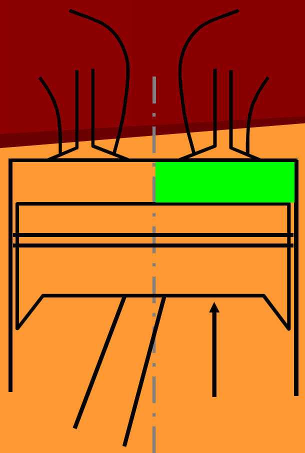
A proposed new engine: HCCI

(homogeneous charge compression ignition)

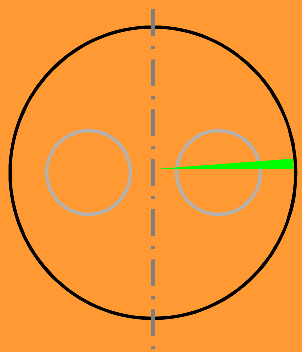


	Gasoline SI	Diesel	HCCI
Premixed?	✓	✗	✓
CI?	✗	✓	✓
Ignition	Spark	Injection	Chemistry
Peak T	Hot: NO_x	Hot: NO_x	Cool

Temperature Distribution Strongly Affects Ignition Chemistry

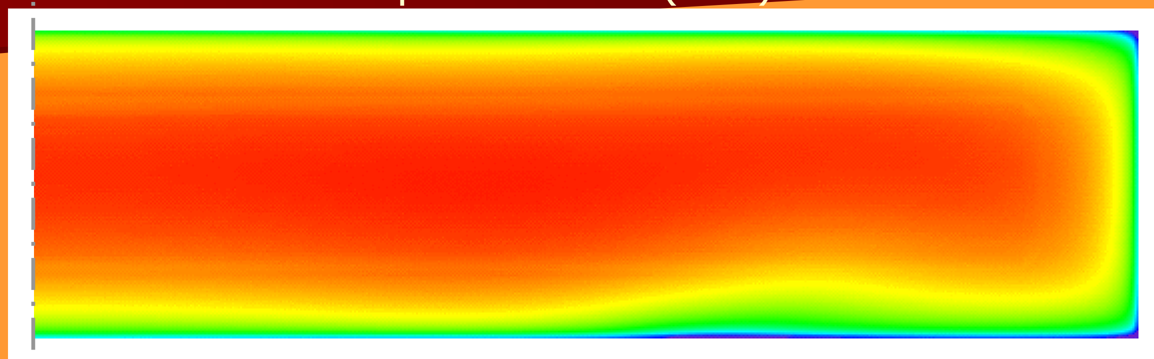


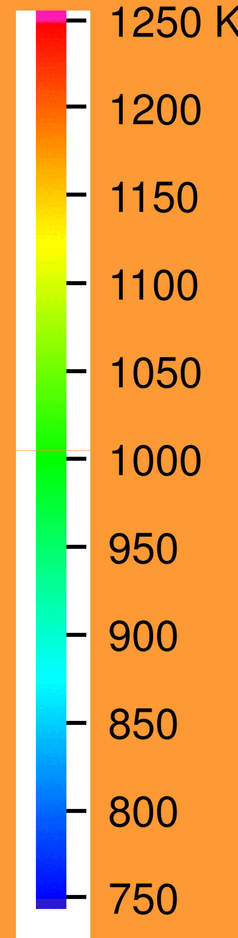
Side View



Top View

Temperature field (TDC)

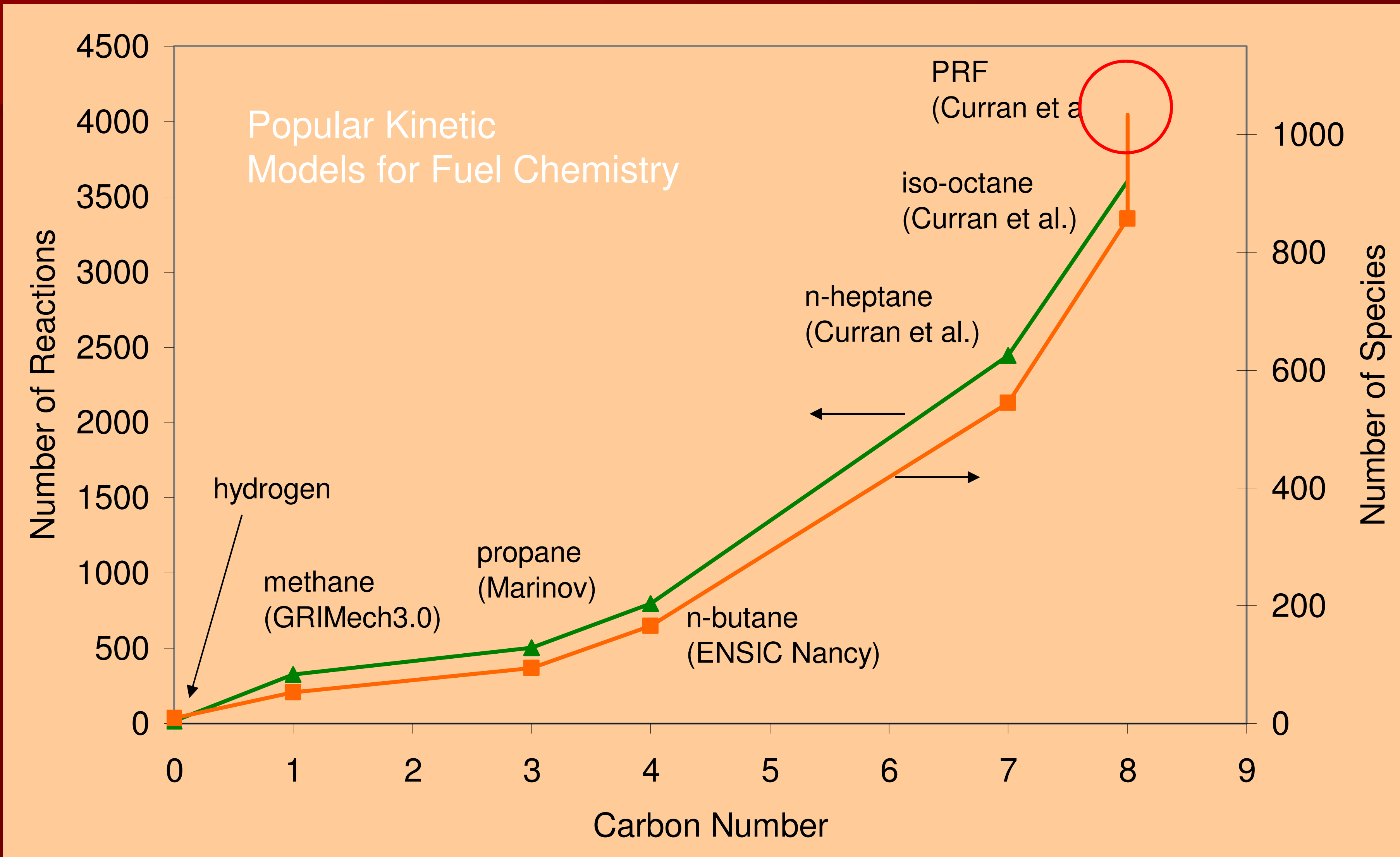




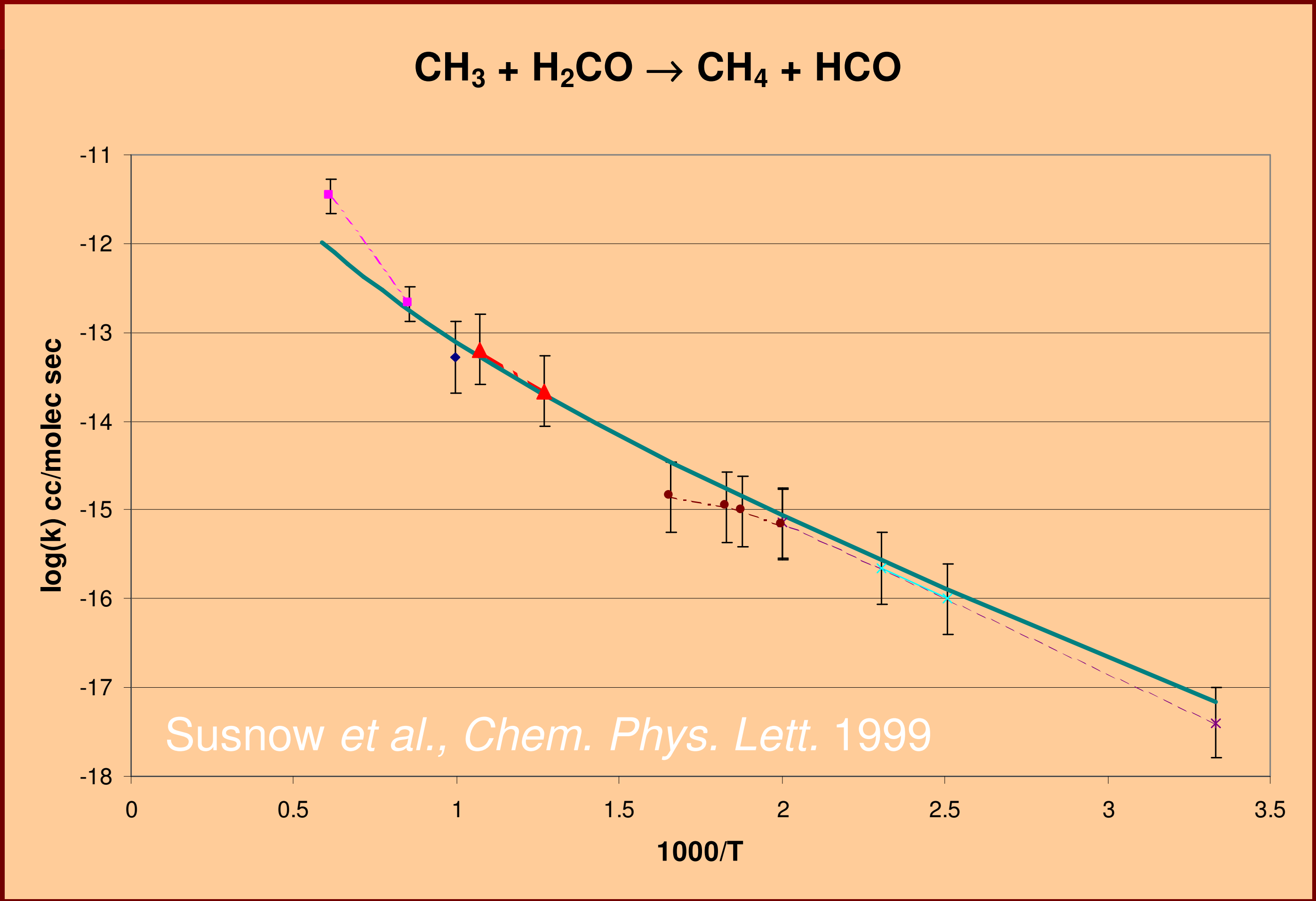
- Basis:
  - 2-d calculation (pancake cylinder)
  - no chemistry
  - working fluid is pure air
  - thermal correction applied later
- Mesh:
  - 160 x 190 grid
  - coarser mesh in core
  - fine mesh in BL (60 μm spacing)

Calcs using KIVA, by A. Amsden, LANL

Chemistry can be *quite* complex



Each chemical reaction has its own (complicated) story



What Speed-Load Range can this HCCI engine deliver?

Figure removed due to copyright restrictions. See Figure 14 in Yelvington, Paul E., et al. "Prediction of Performance Maps for Homogenenous-Charge Complression-Ignition Engines." *Combustion Science and Technology* 176 (August 2004): 1243-1282.

Fuel = n-heptane

C.R.=9.5

Boost = 0.7 bar

Yelvington et al., *Combust. Sci. Tech.* (2004).

Integrating engine's performance over the driving cycle

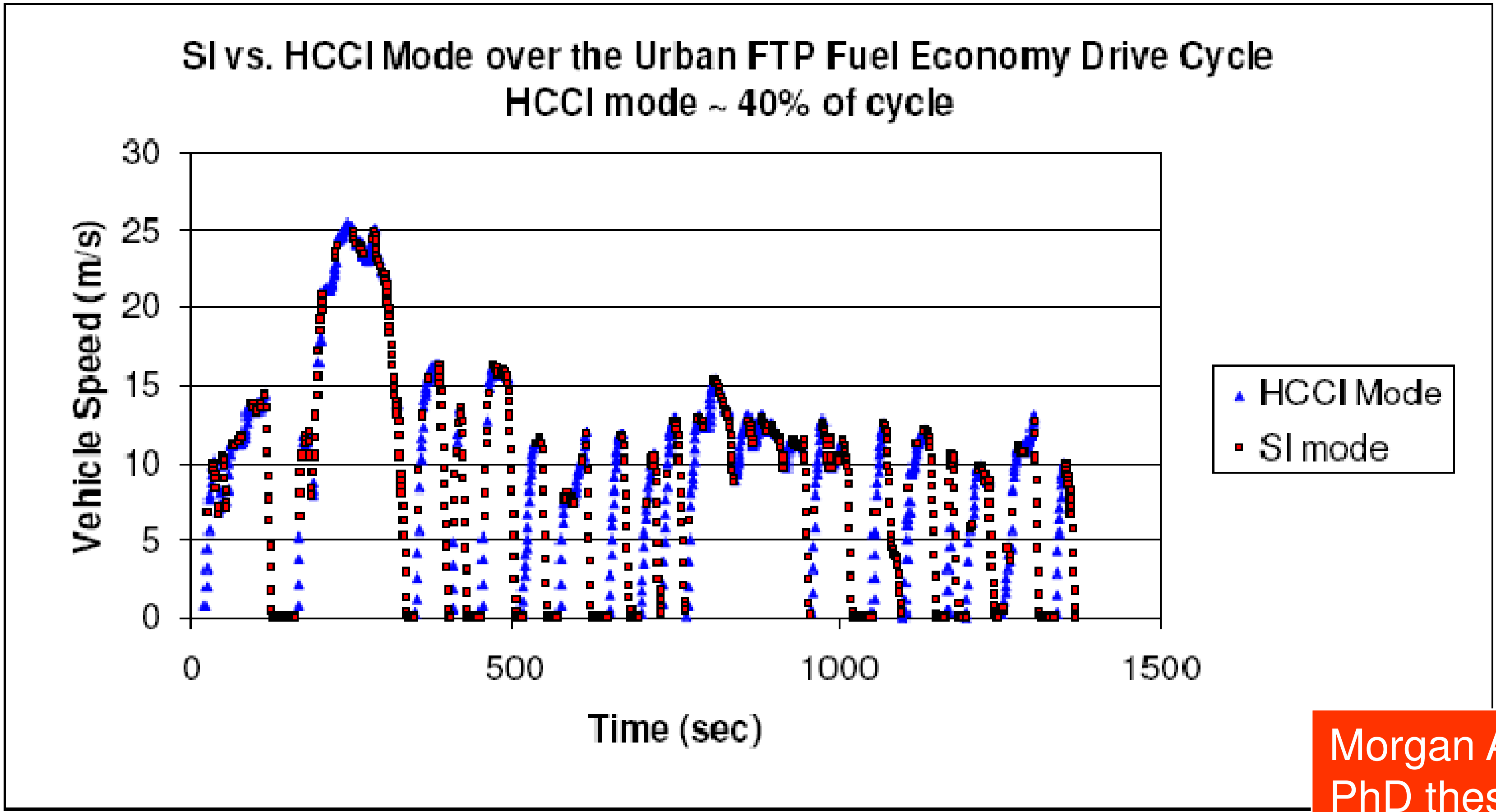


Figure 5.3. Vehicle speed versus time for the FTP Urban Drive Cycle.

Morgan Andreae
PhD thesis 2006

With this information,

can estimate mpg for new engine/fuel combo

22.081J / 2.650J / 10.291J / 1.818J / 2.65J / 10.391J / 11.371J / 22.811J / ESD.166J
Introduction to Sustainable Energy
Fall 2010