

# Why Electrify?

## Towards a New Paradigm for Transportation's Energy Transition

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Transportation Electrification Workshop

Transportation Center -- Northwestern University

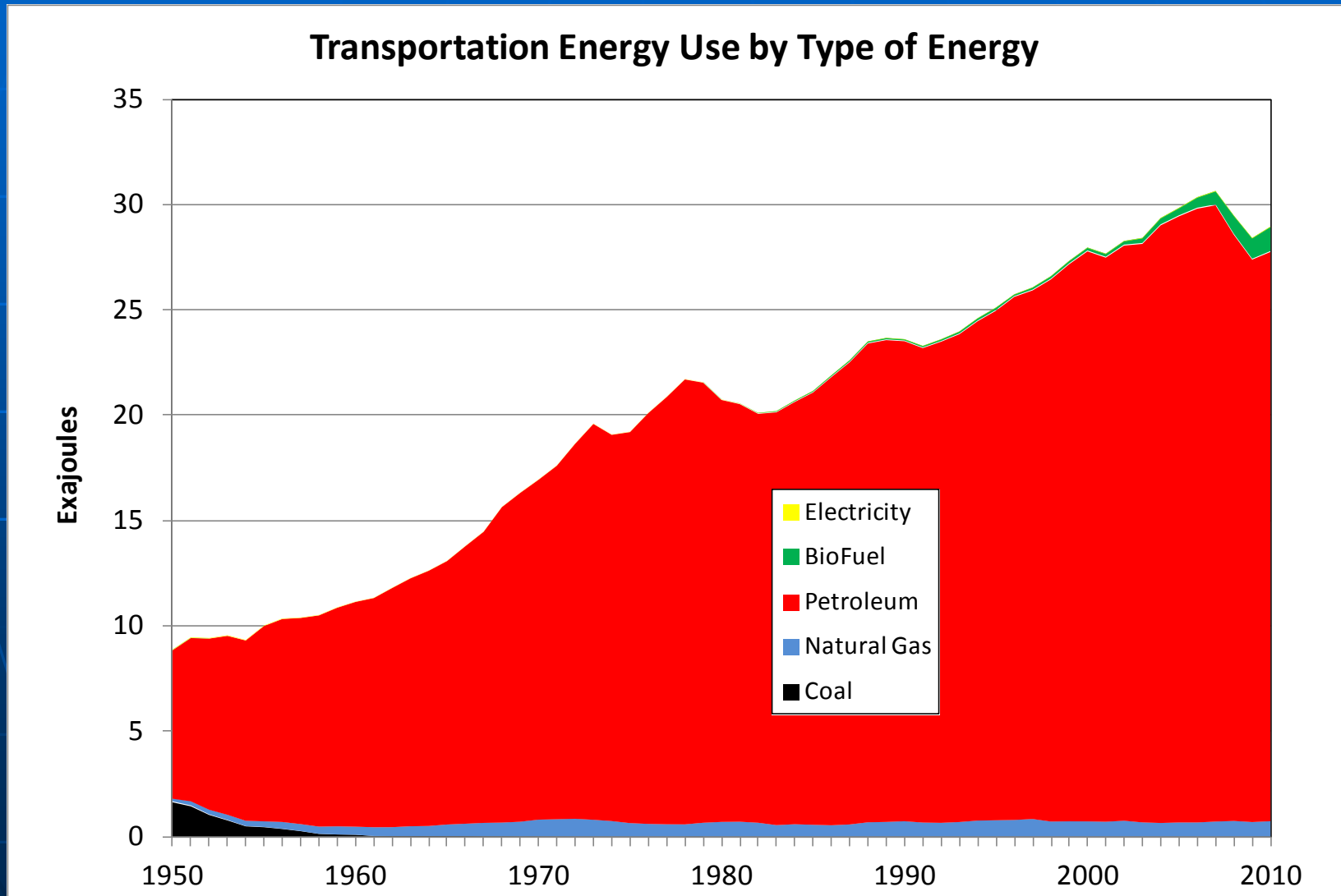
Evanston, Illinois

April 18, 2012

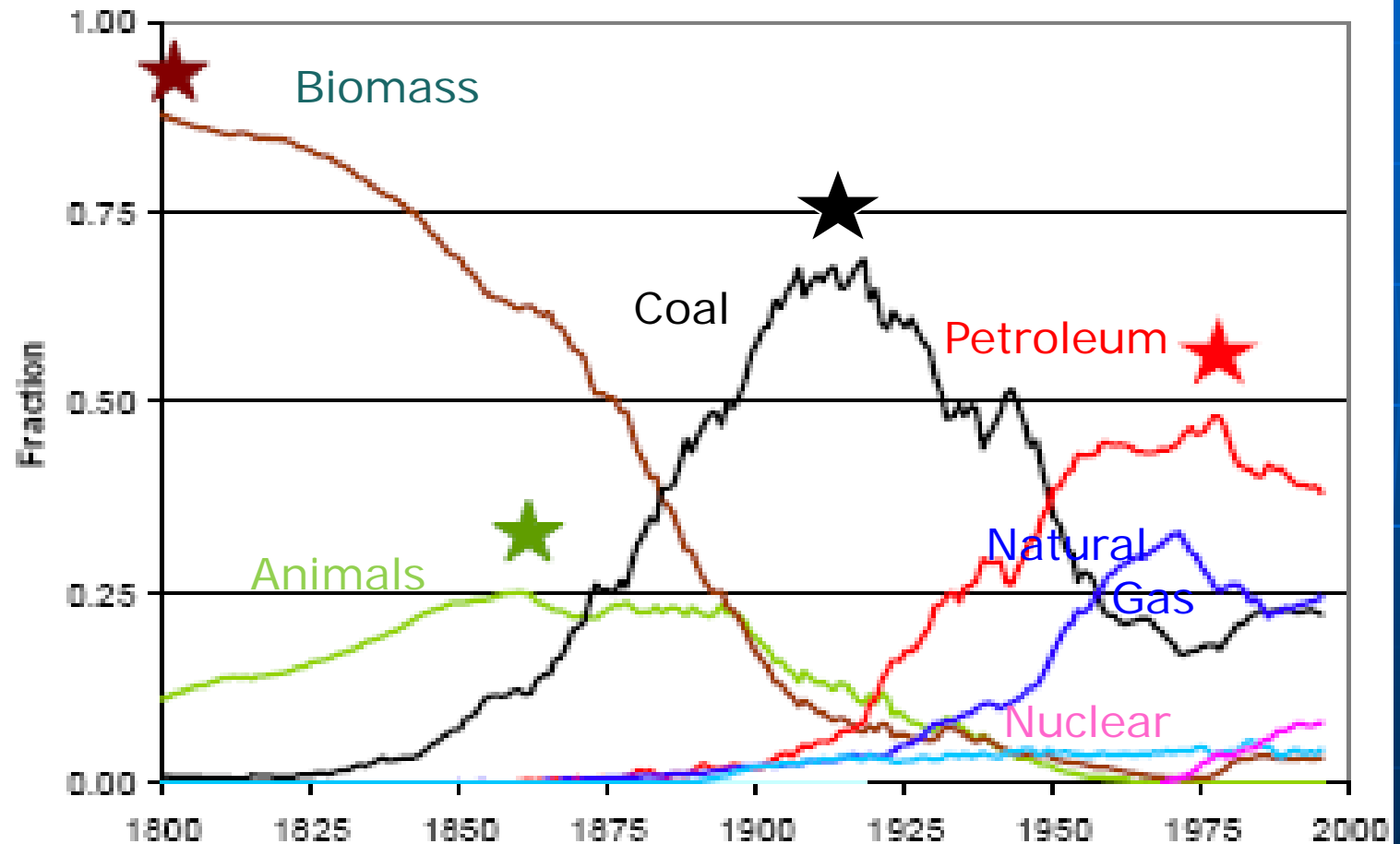
Thesis: We lack a public policy paradigm and the analytical tools to manage a large scale energy transition to electric drive (for the public good).

- Externalities are not the core problem.
- Technological outcomes are uncertain.
- Energy prices are uncertain.
- Size of market barriers is uncertain.
- Consumer values are uncertain.
- Value of public goods also uncertain.
- And yet, solutions appear to require urgent, transforming action.

The petroleum-fueled, internal combustion engine powered transportation system has been “locked in” by a century of learning, technological evolution and investment.



The great energy transformations of the past were driven by technological change and market forces.  
Creating a transition for the public good poses a new challenge.

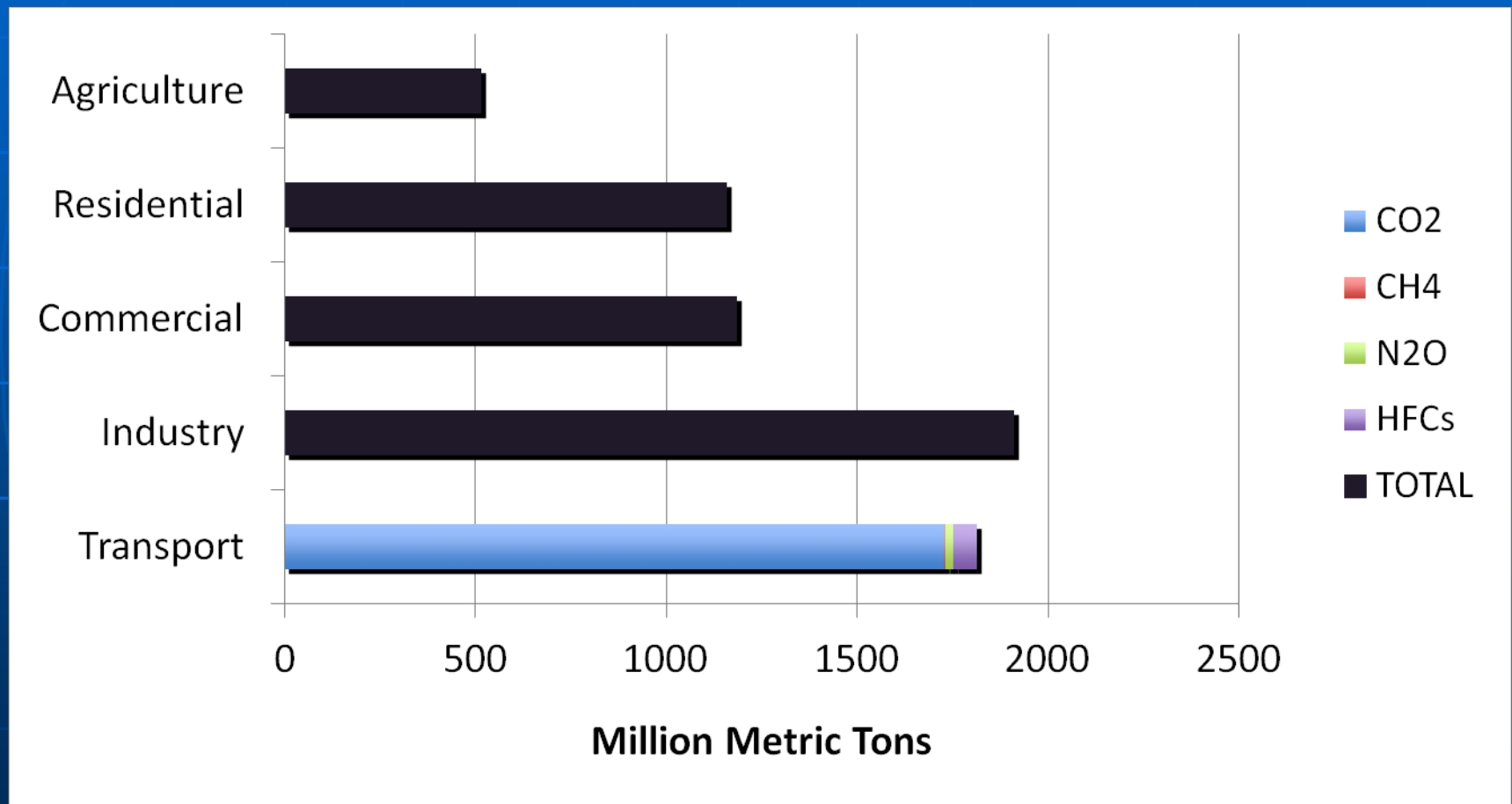


Source: A. Grubler, 2007, International Institute for Applied Systems Analysis.

# The old ideas are inadequate.

- Creating an energy transition for the public good:
  - Avoid dangerous climate change
  - Achieve energy security
  - Create a sustainable energy system
- New paradigm is needed
  - Cannot rely on market forces to displace "locked-in" OIL-ICE system
  - Internalizing external costs not sufficient
  - Possibilities, costs & benefits highly uncertain

The U.S. transportation system emits more CO<sub>2</sub> than any country's entire economy except China.



The 2009 joint statement by the National Academies of Science of the G8+5 is strongly worded and endorses a 50% reduction in global emissions vs. 1990 levels by 2050.

"The IPCC 2007 Fourth Assessment of climate change science concluded that large reductions in the emissions of greenhouse gases, principally CO<sub>2</sub>, are needed soon to slow the increase of atmospheric concentrations, and avoid reaching unacceptable levels. However, *climate change is happening even faster than previously estimated*; global CO<sub>2</sub> emissions since 2000 have been higher than even the highest predictions, Arctic sea ice has been melting at rates much faster than predicted, and the rise in the sea level has become more rapid. Feedbacks in the climate system might lead to much more rapid climate changes. *The need for urgent action to address climate change is now indisputable*. For example, limiting global warming to 2° C would require a very rapid worldwide implementation of all currently available low carbon technologies." (May 2009)

Emphasis added by me.



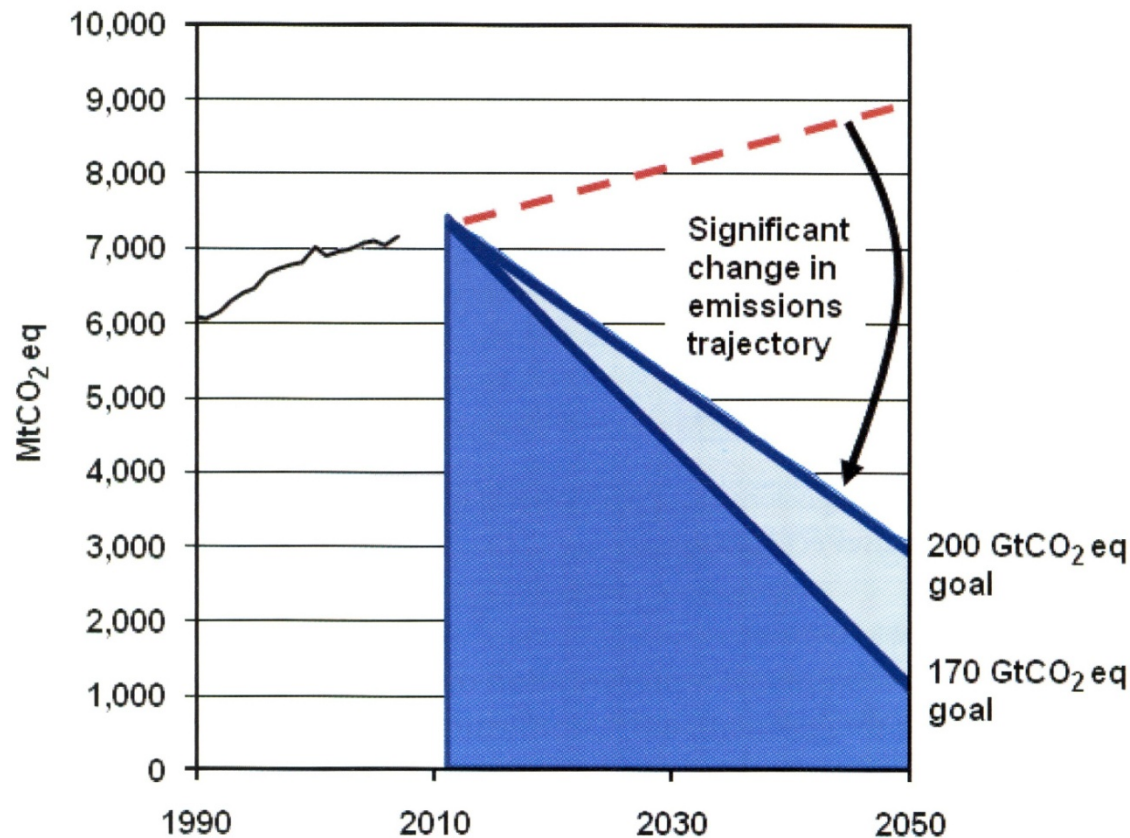
Reducing global transportation energy intensity by 50% or more could hold energy use at today's level in 2050.  
**But we need to reduce GHG emissions to 50% or more below today's level.**

Table 1. Impact of Transport Energy Efficiency Improvement on Energy Use in 2050 (Exajoules)

Mode	Energy Use 2007	Growth Rate %	Extrapolated Energy Use 2050	Efficiency Improvement (% reduction)	Efficient Energy Use 2050	Energy Use With Rebound 2050
Road	103	2.0%	241	70%	72	87
Air	11	3.0%	39	60%	16	18
Water	9	2.0%	21	50%	11	12
Rail	5	1.0%	8	50%	4	4
TOTAL	128		309		102	121

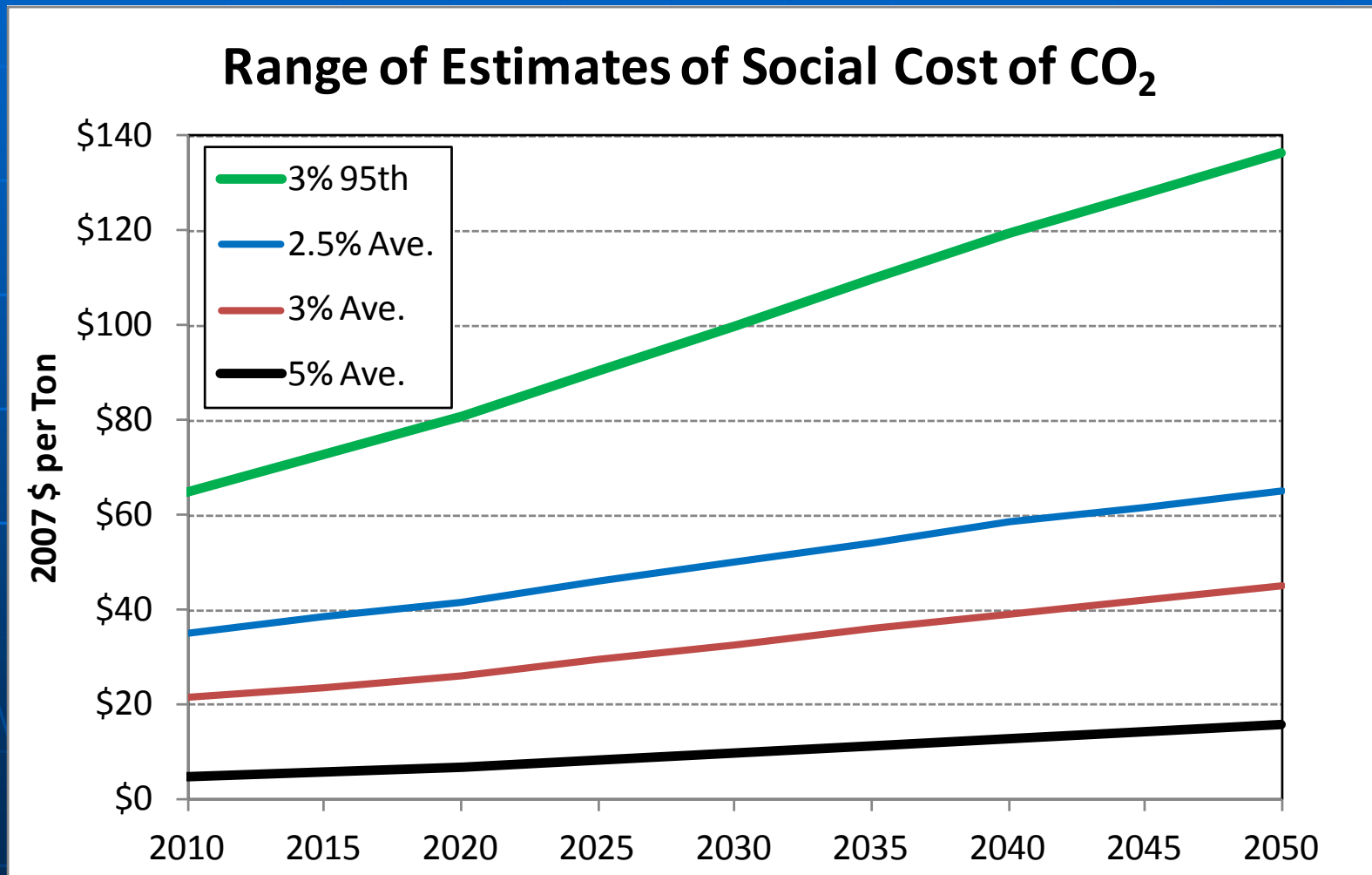


NAS: limiting the global average temperature rise to 2°C (avoid dangerous climate change) implies the U.S. limits its C emissions to 170 GtCO<sub>2</sub> eq.



**FIGURE 2.10** Illustration of the representative U.S. cumulative GHG emissions budget targets: 170 and 200 Gt CO<sub>2</sub>-eq (for Kyoto gases) (Gt, gigatons, or billion tons; Mt, megatons, or million tons). The exact value of the reference budget is uncertain, but nonetheless illustrates a clear need for a major departure from business as usual.

But how much should we spend? 2010 U.S. Government interagency study recommends a range of estimates of potential damages (p. 33): from \$4.70 to \$64.90 per ton in 2010, up to \$15.70 to \$136.20 in 2050.



Interagency Working Group on the Social Costs of Carbon, U.S. Government, Feb., 2010.

# What is oil dependence?

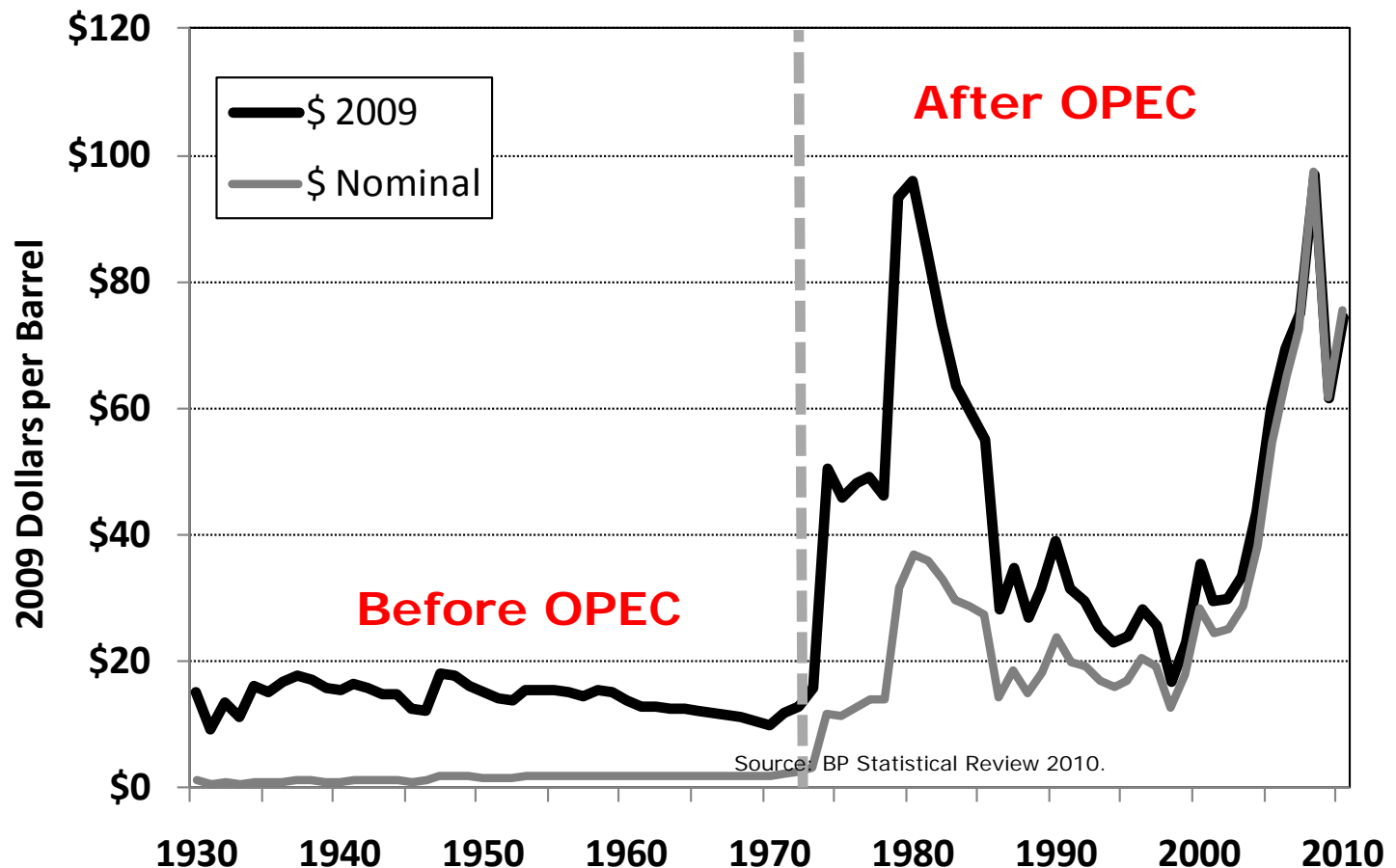
Oil dependence is primarily an economic problem with significant national security implications caused by,

- importance of oil to the economy and,
- lack of economical substitutes for oil,
- use of market power by oil producers.
- It is NOT an externality.

“The real problem we face over oil dates from after 1970: a strong but clumsy monopoly of mostly Middle Eastern exporters operating as OPEC.” Prof. M. Adelman, MIT, 2004.

[Algeria](#)  
[Angola](#)  
[Ecuador](#)  
[Iran](#)  
[Iraq](#)  
[Kuwait](#)  
[Libya](#)  
[Nigeria](#)  
[Qatar](#)  
[Saudi Arabia](#)  
[UAE](#)  
[Venezuela](#)

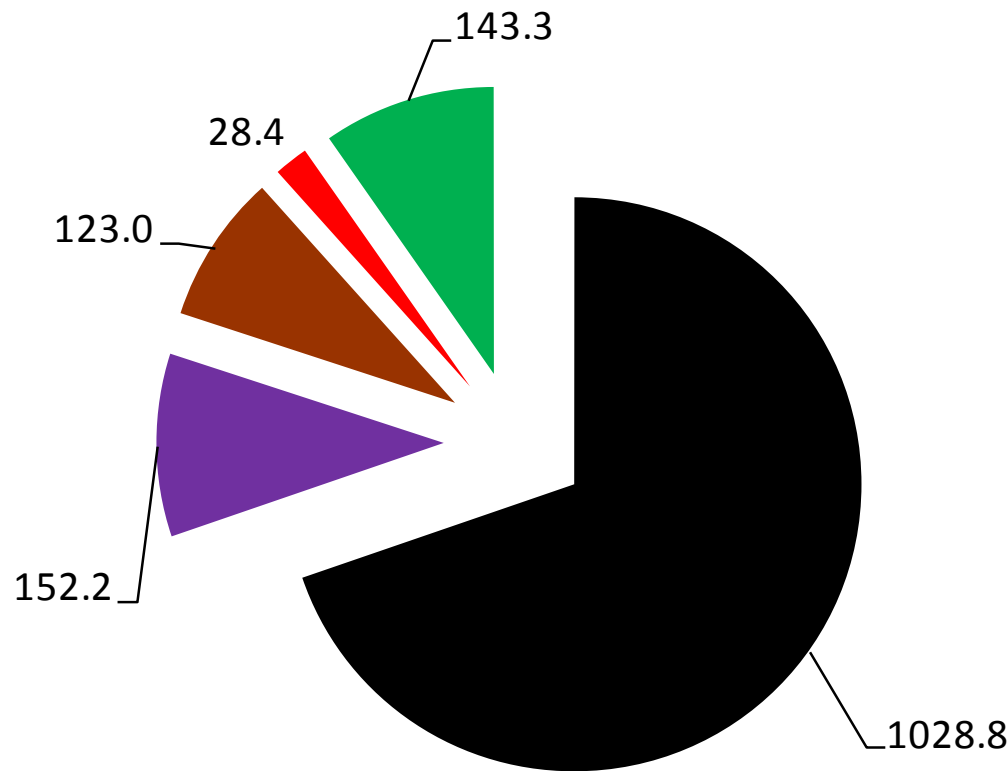
## World Crude Oil Prices, 1930-2010



## Who are the oil producers?

OPEC members own 70% of the world's proven oil reserves and >50% of the ultimate resources of conventional oil.

National oil companies own more than 80%.



■ OPEC ■ Non-OPEC ■ Former USSR ■ USA ■ Canada Oil Sands

The economic theory to understand the behavior of the OPEC oil cartel was developed more than half a century ago by Heinrich von Stackelberg.

$$P = \frac{C}{1 + \left( \frac{1}{\beta(P)} S(\mu(P) + 1) \right)}$$

$\beta$  = price elasticity of world oil demand (  $\beta < 0$  )

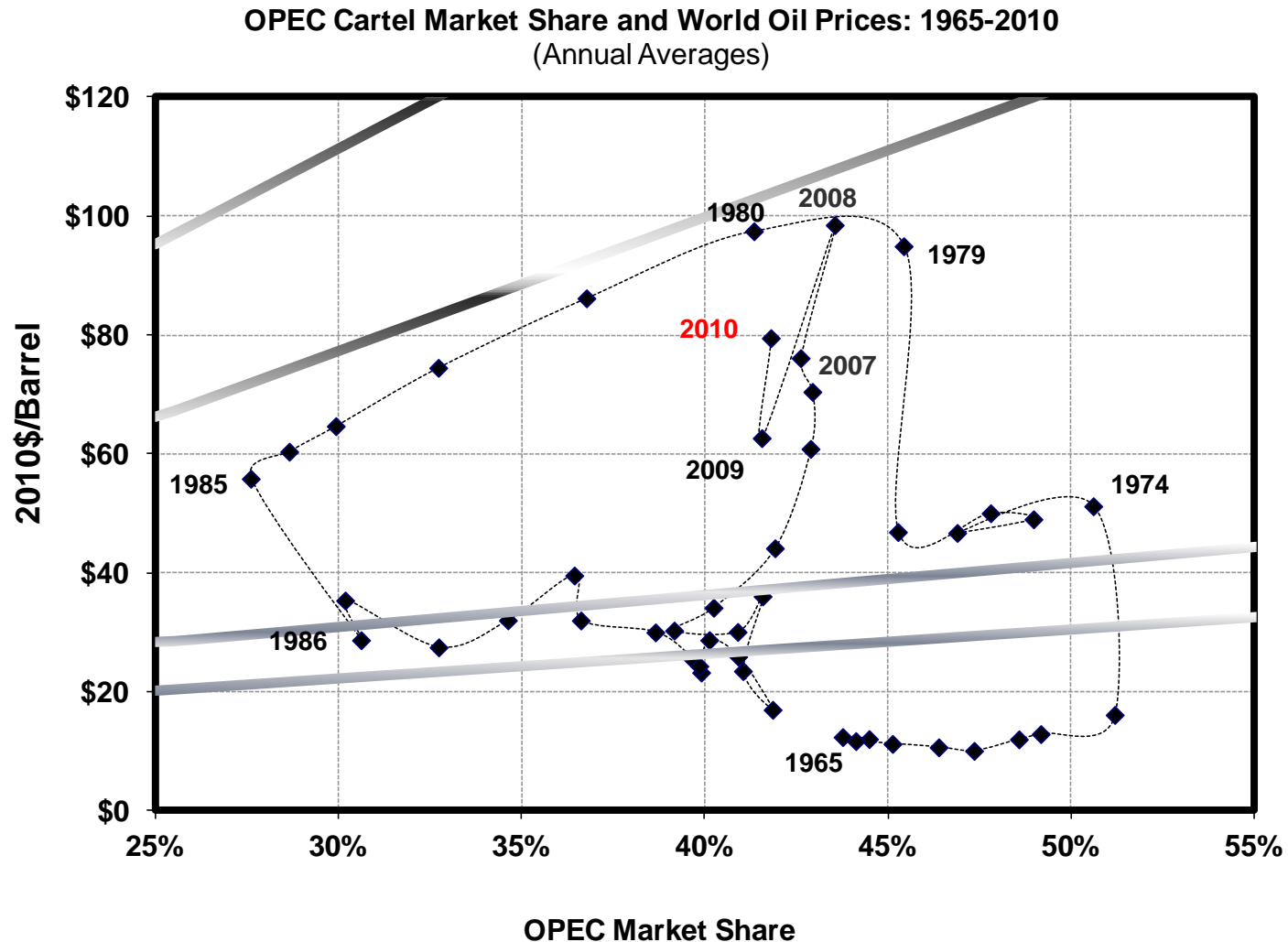
$S$  = OPEC share of world oil market (  $0 < S < 1$  )

$\mu$  = non-OPEC supply response (  $-1 < \mu < 0$  )

Elasticity = % change in quantity / % change in price =  $d \ln(y)/d \ln(x)$

**Short- and long-run elasticities differ by an order of magnitude!**

The “random walk” of oil prices since 1974 takes place within the partial monopoly framework.



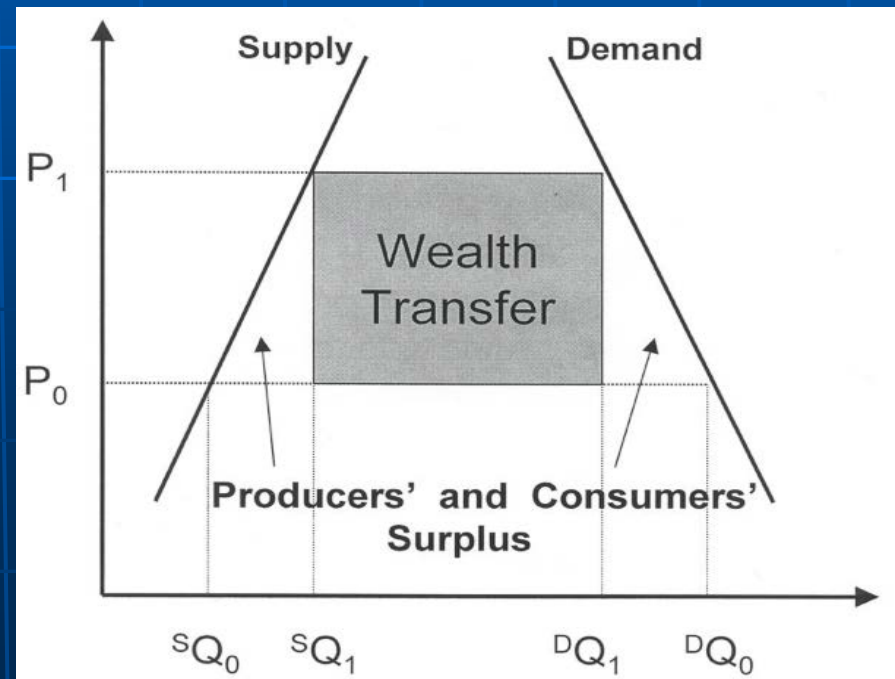
Source: 1965-2010 BP Statistical Review 2010. Oil Production - barrels and Oil - crude oil prices since 1861.



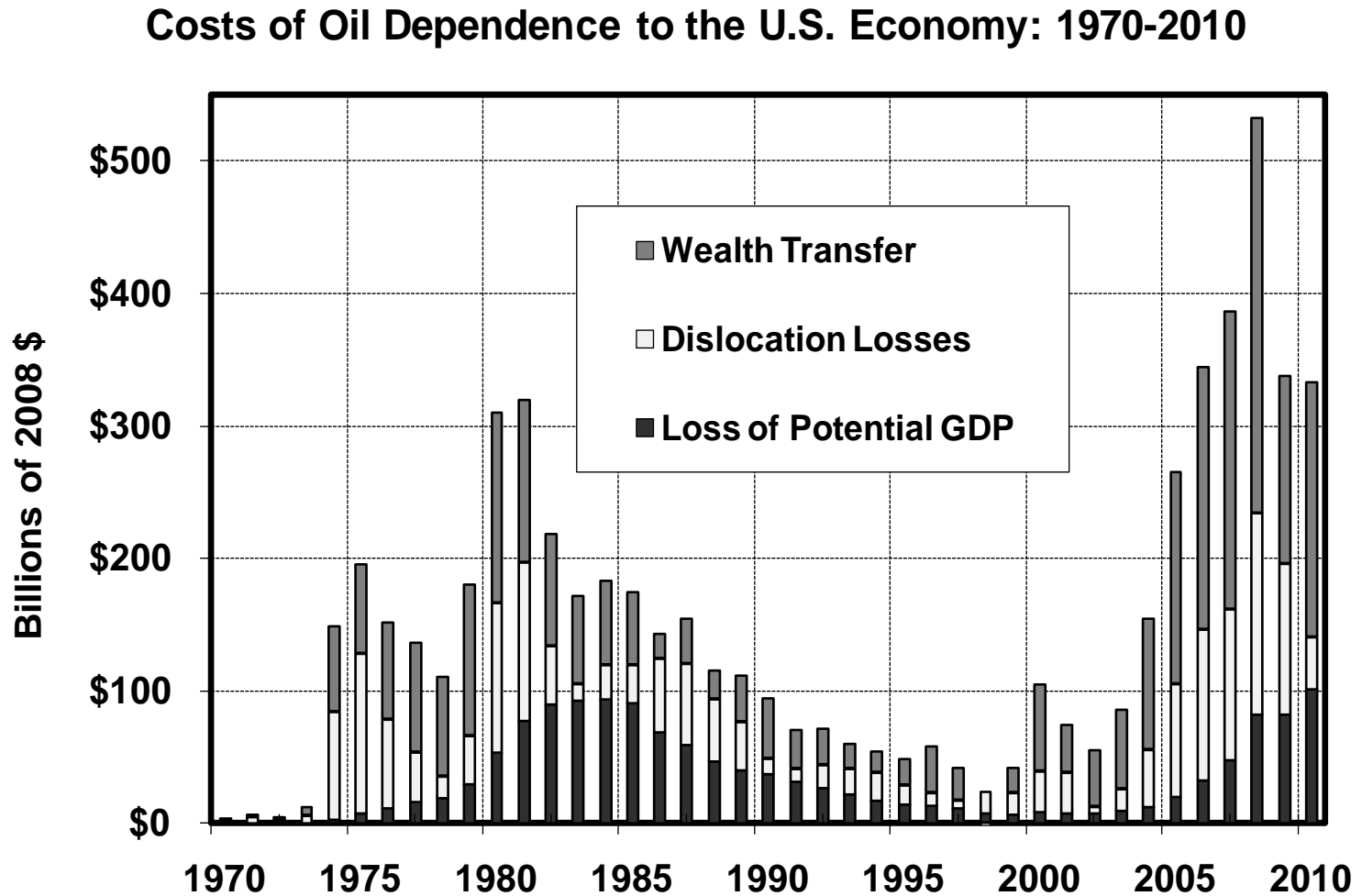
# What does oil dependence cost?

1. **Loss of potential GDP** = producers' & consumers' surplus losses in oil markets (dynamic).
2. **Dislocation losses** of GDP due to oil price shocks.
3. **Transfer of wealth** due to monopoly pricing and price shocks (requires counterfactual competitive price).

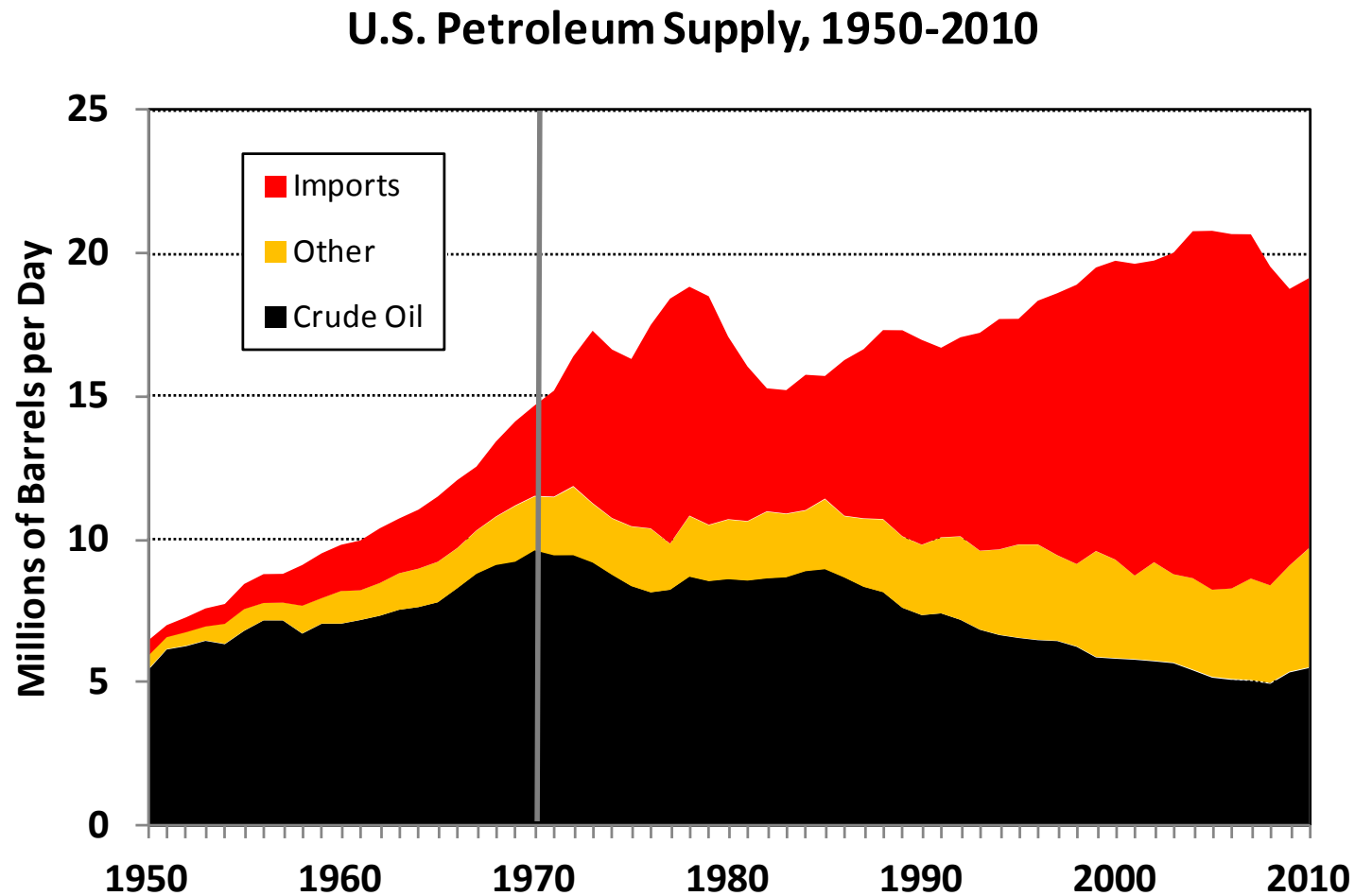
**Transfer of wealth** is not a loss of GDP but a change in the ownership of GDP. It can occur in disrupted and undisrupted markets and occurs whether or not OPEC is the cause of the disruption.



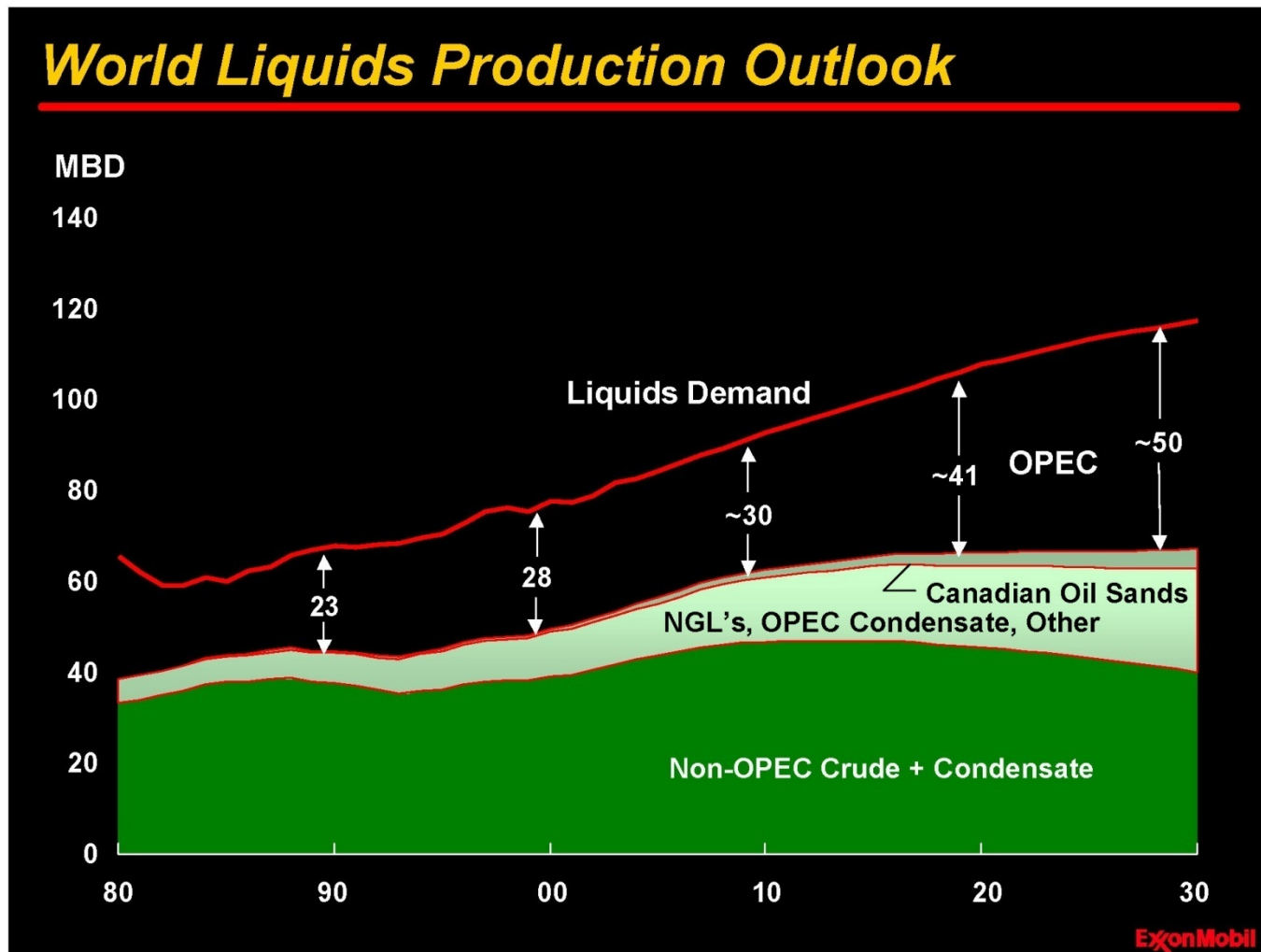
Oil dependence cost the US about \$500 billion in 2008.



The cartel's market power was strengthened by growing world demand, its increasing market share and...the **peaking of US crude oil production in 1970**.

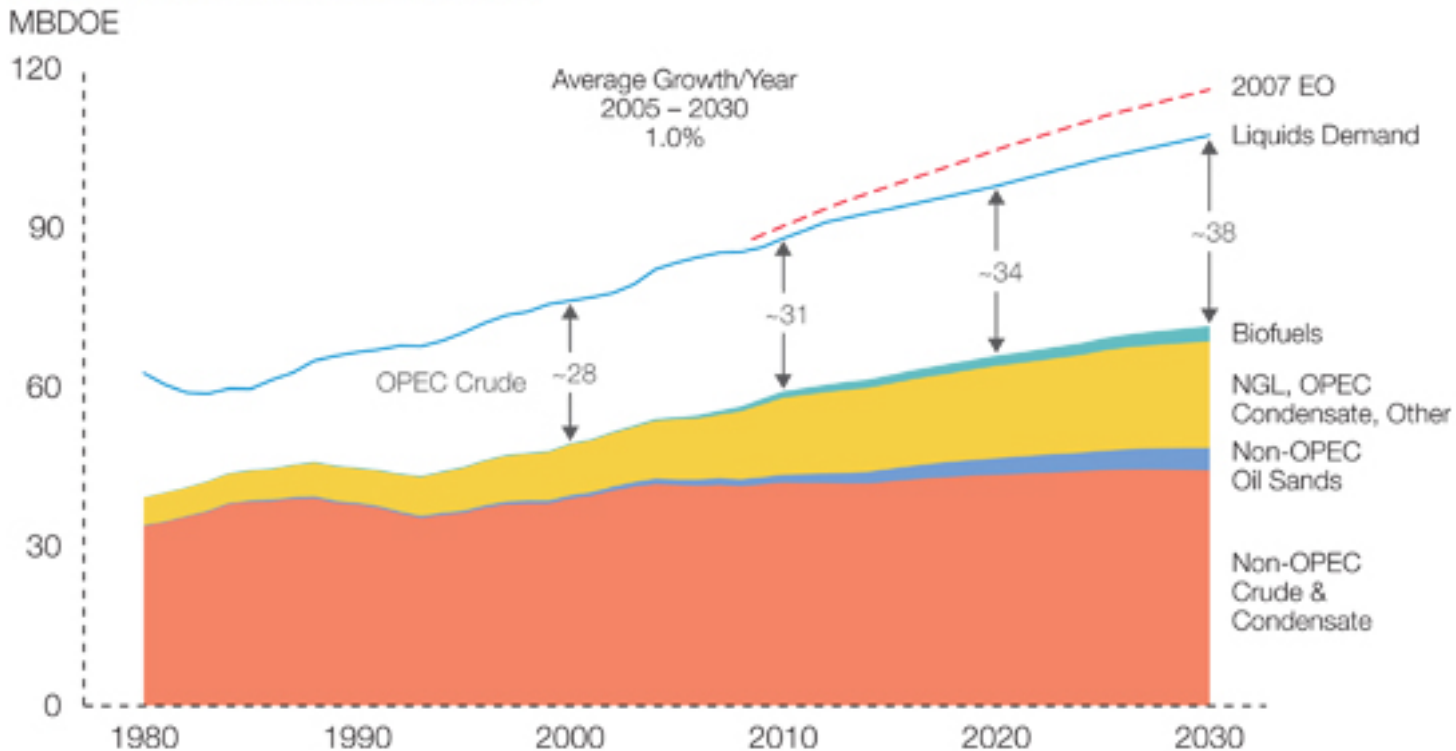


Projections of just 5 years ago expected peaking of non-OPEC supply with OPEC filling the gap.  
Didn't happen; won't happen.



ExxonMobil's current energy outlook, reflecting oil prices in the vicinity of \$100/barrel, is not much more optimistic about non-OPEC crude oil supply.

### global liquids supply and demand

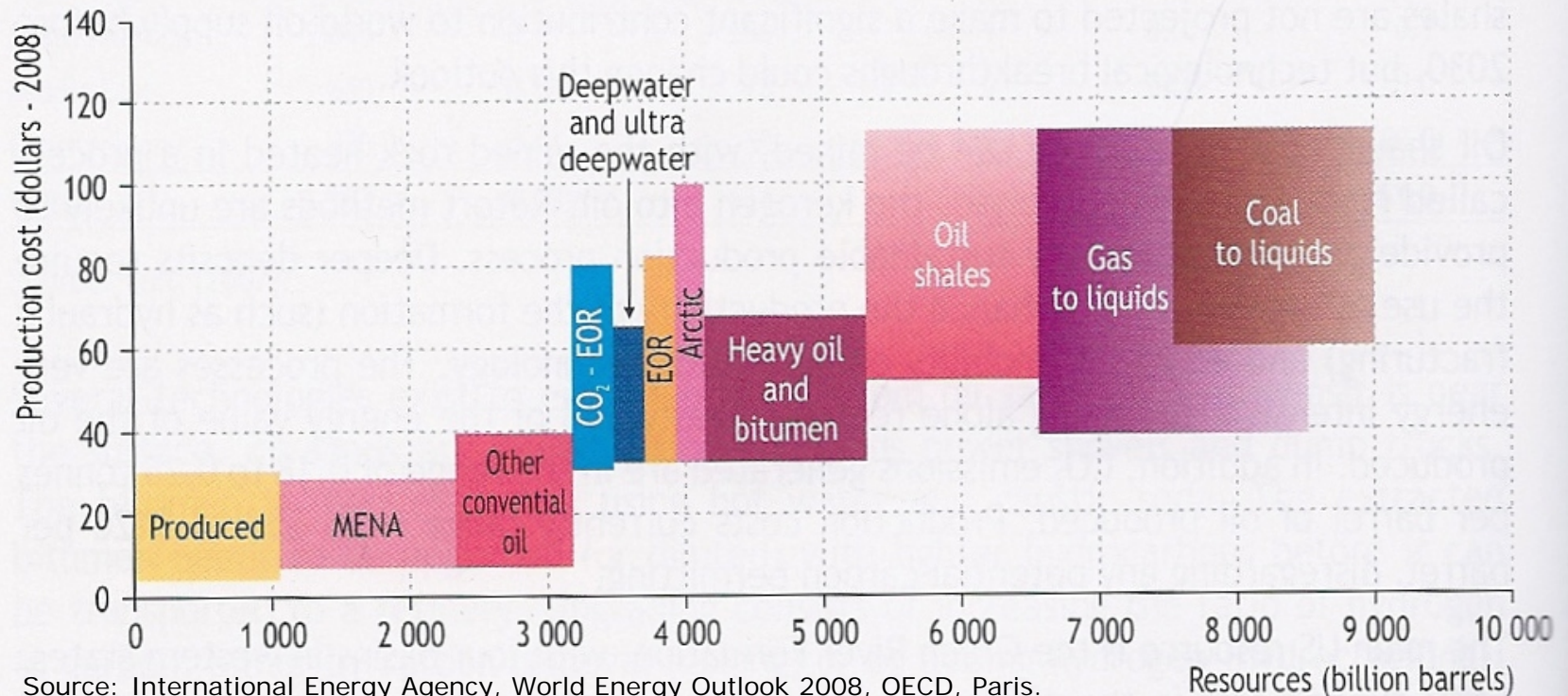


Source: ExxonMobil, The outlook for energy: a view to 2030, January 14, 2009.  
[http://www.exxonmobil.com/Corporate/energy\\_outlook.aspx](http://www.exxonmobil.com/Corporate/energy_outlook.aspx)



Continuing current trends, the world will have used well over half of all conventional oil resources before 2050. The **path of least resistance** is fuels from unconventional fossil resources at prices the world is willing to pay.

**Figure 9.10 • Long-term oil-supply cost curve**



# Carbon Reservoirs

Atmosphere 800 GtC (2004)

Biomass  
~500 GtC

N. Gas  
~260 GtC

Oil  
~270 GtC

Soils  
~1,500 GtC

Coal  
5,000 to 8,000 GtC

Source: Edmonds, 2005

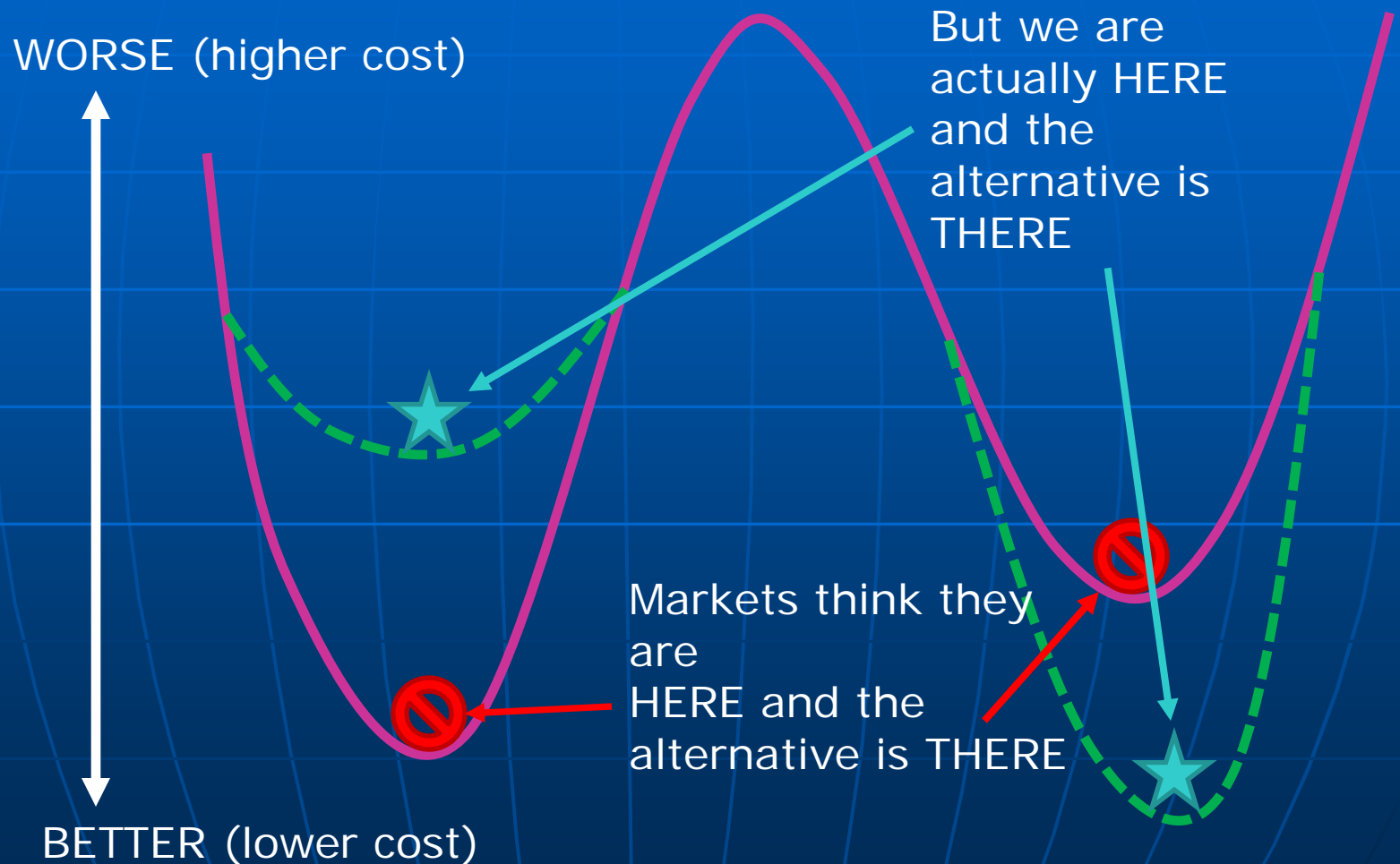
Unconventional Fossil Fuels  
15,000 to 40,000 GtC



# There are real economic barriers to displacing the incumbent technology.

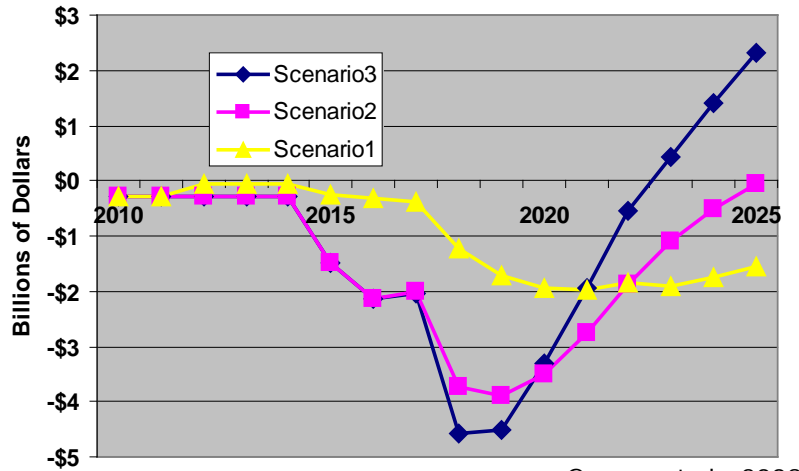
- Scale economies
- Learning by doing
- Lack of choice diversity
- Risk aversion
- Fuel availability/demand
- Uncertainty of technological change
- Petroleum price response
- + market imperfections
  - Externalities
  - Energy efficiency paradox (behavioral economics)
  - Oil price volatility due to monopoly power

Can this problem be solved by internalizing externalities? Maybe, but probably not.



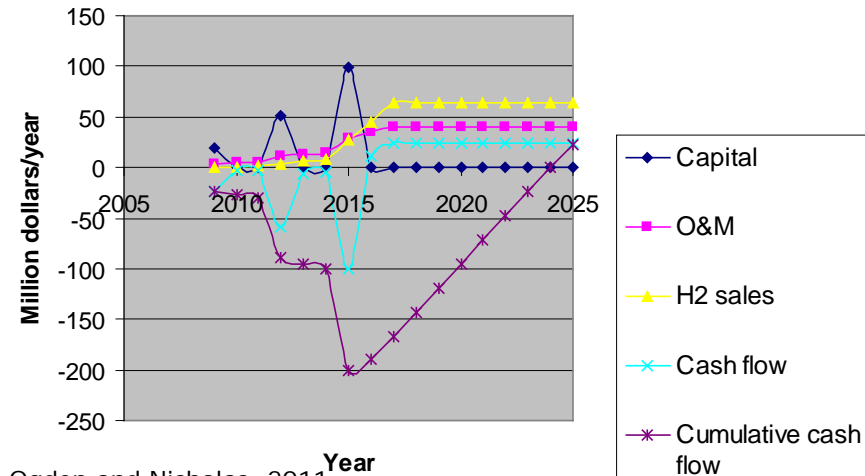
# Upfront costs of an energy transition can delay or prevent the transition, yet they appear to be small relative to total potential social benefits.

**Simulated Auto Industry Cash Flow From Sale of Hydrogen Fuel Cell Vehicles, No Policy Case**



Greene et al., 2008

**Cash Flow for H2 Transition Scenario**



Ogden and Nicholas, 2011.

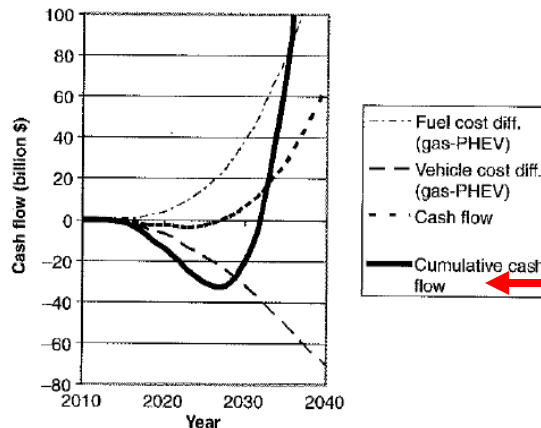


FIGURE 4.10 Cash flow analysis for PHEV-10, Maximum Practical Case, Optimistic technical assumptions. The break-even year is 2028, and the buydown cost is \$33 billion.

**NRC 2008**

**NRC 2010**

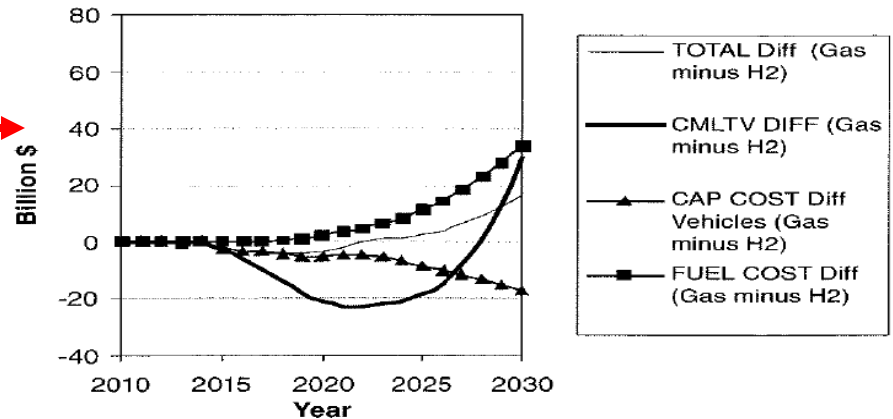


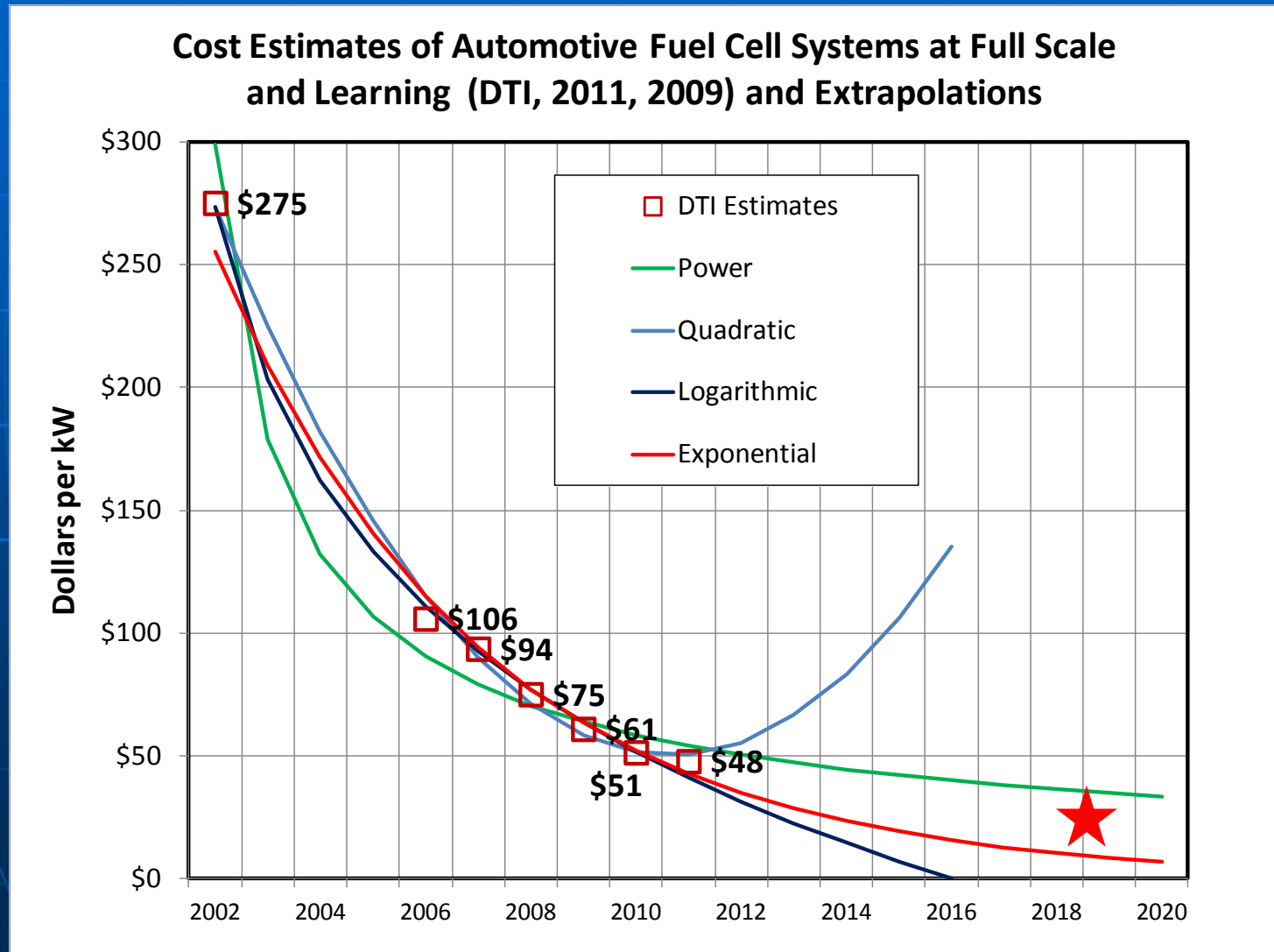


FIGURE 6.13 Cash flows for Case 1.

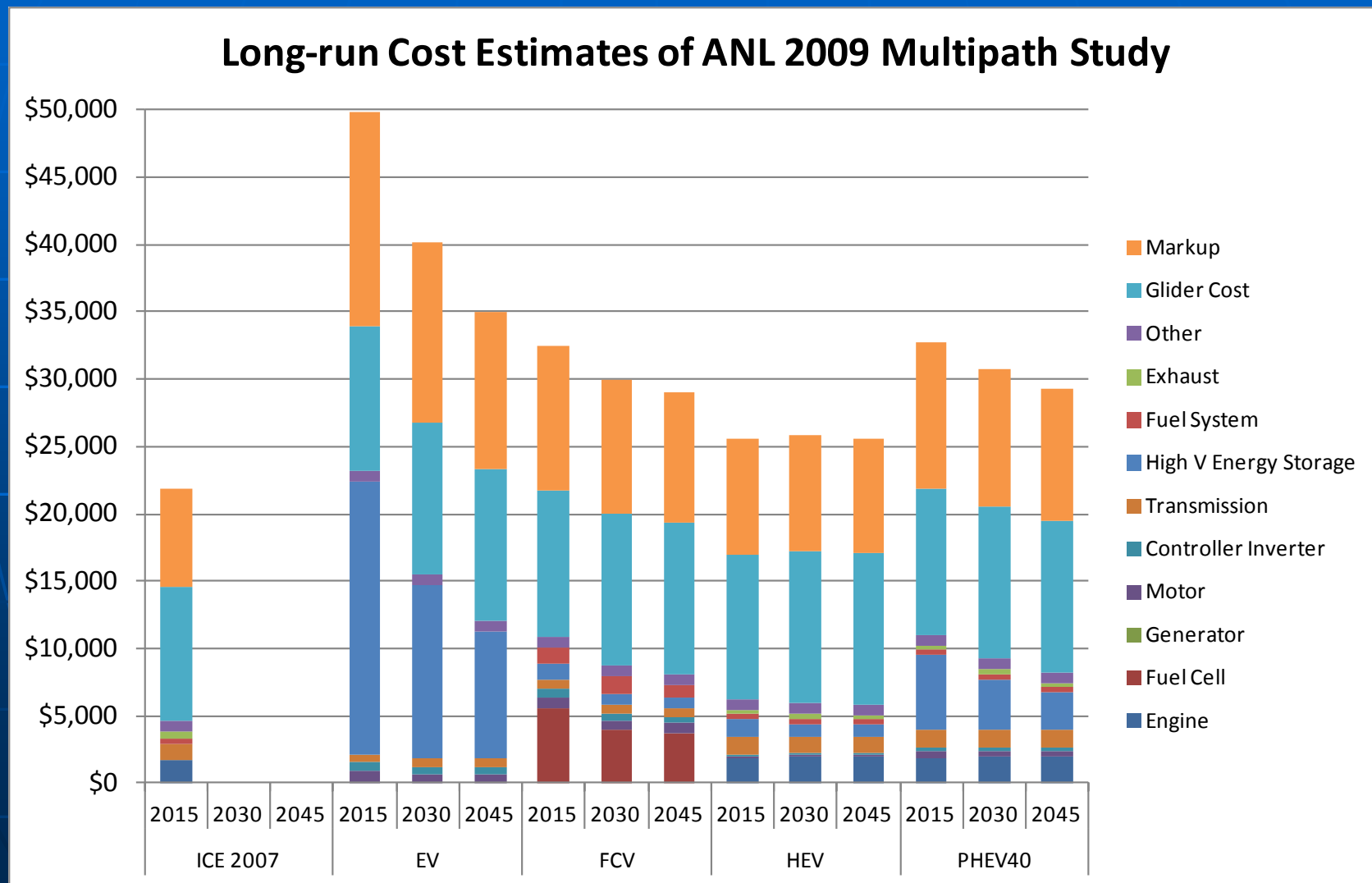
# Is a transition to zero emission vehicles worth it?

- ❖ Based on the NRC 2009 "maximum practicable" hydrogen fuel cell vehicles study.
  - ❖ Rough estimation based on figures 6.32 and 6.33:
    - ❖ Approx. 20 billion tons cumulative CO<sub>2</sub> reduction by 2050
    - ❖ Approx. 50 billion barrels of reduced petroleum consumption
  - ❖ Converting to dollars & *undiscounted*:
    - ❖ CO<sub>2</sub> at \$50/ton  \$1 Trillion
    - ❖ Oil security at \$20/bbl  \$1 Trillion
- ❖ Very roughly, estimated excess cost of transition appears to be an order of magnitude smaller than the estimated value of public benefits (*subject to many assumptions and predictions*).

# The historical progress of fuel cells and batteries is impressive. But what will the future hold?

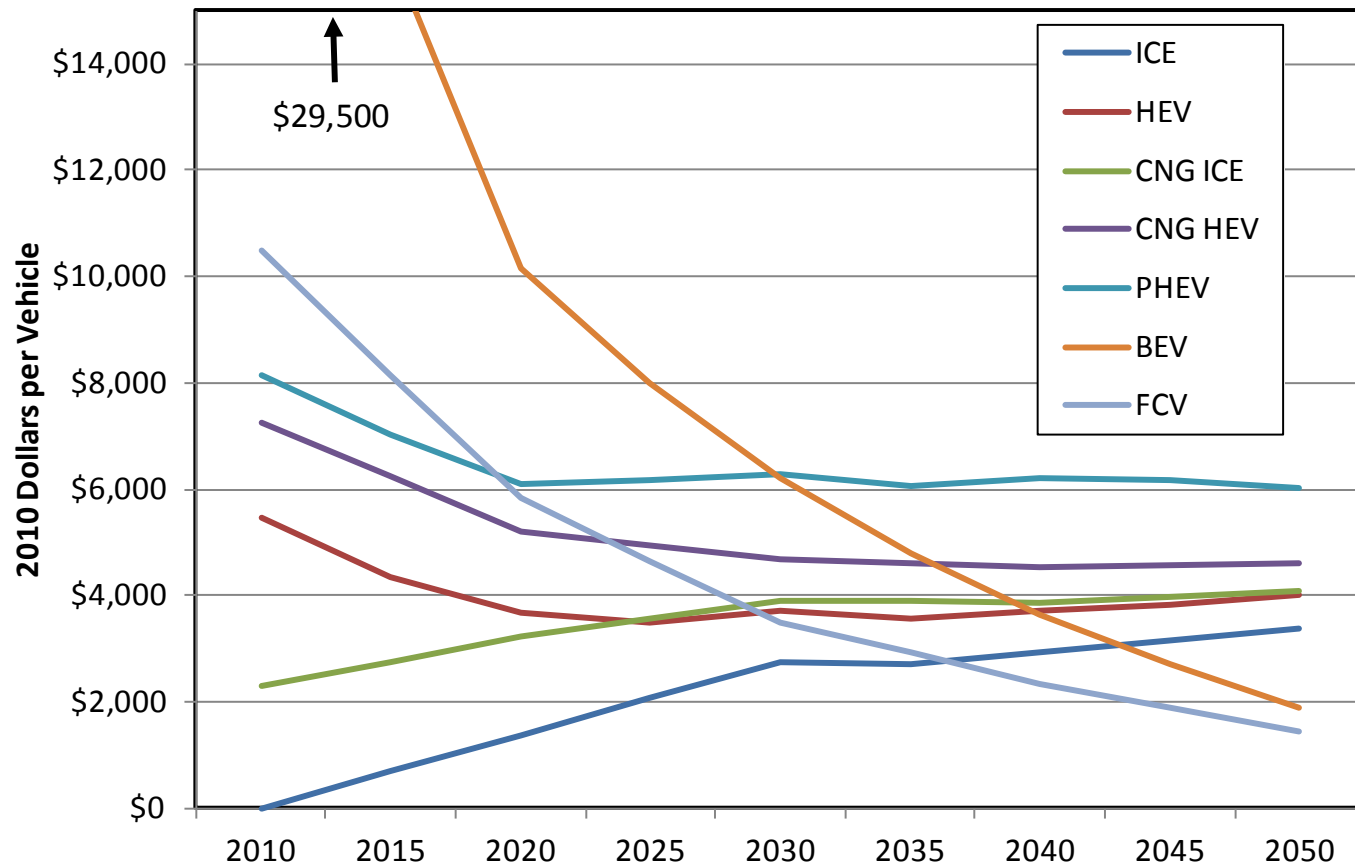


Argonne's Multipath study, like MIT's *On the Road in 2035* foresees gradual improvements in technology but not enough to make their prices less than an ICE.



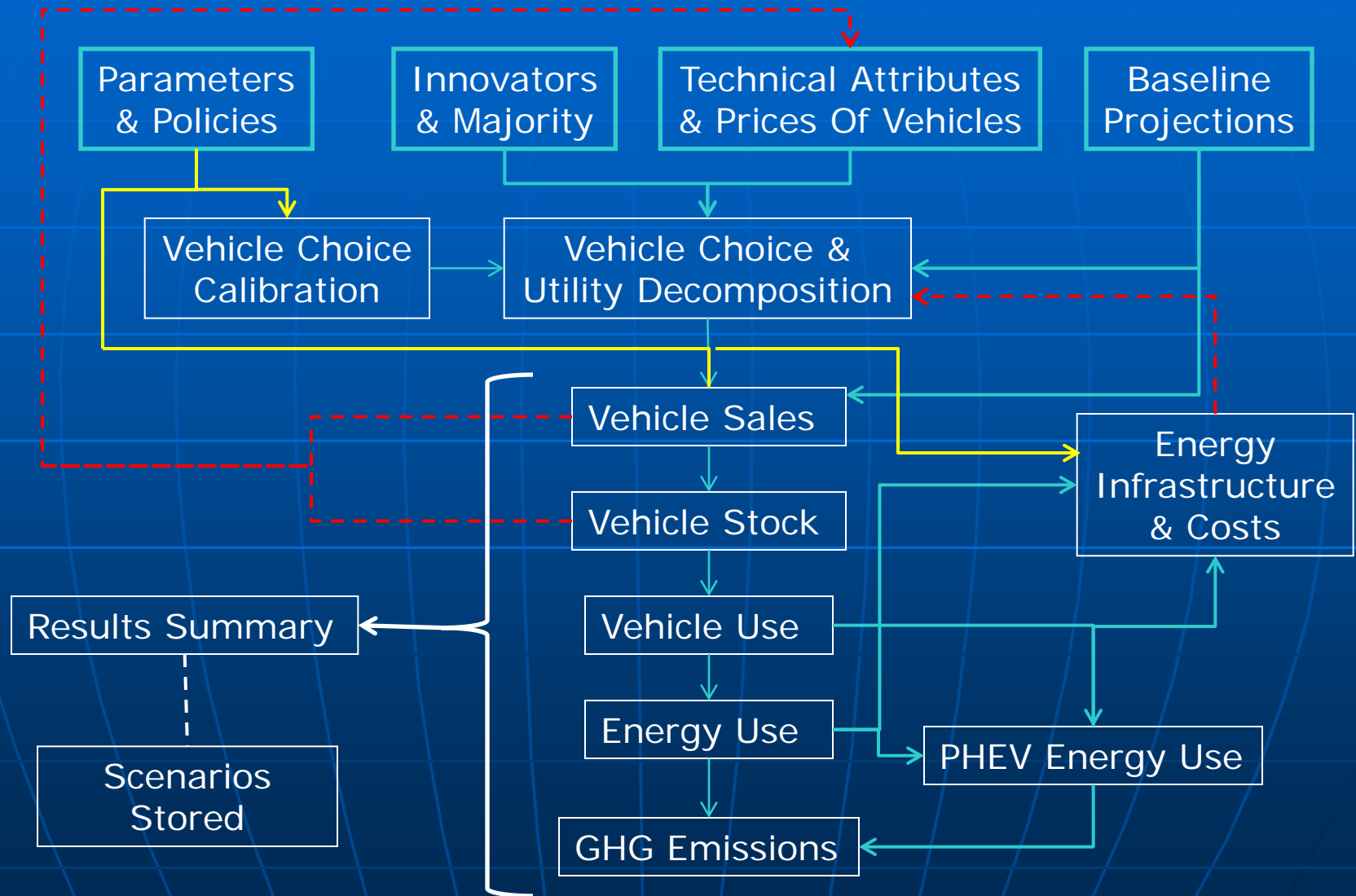
# Other estimates show BEVs and FCVs eventually becoming cheaper than ICEs and HEVs.

Estimated Incremental RPEs for Advanced Technologies  
Expected Progress (German, 2011), 1.3 Markup

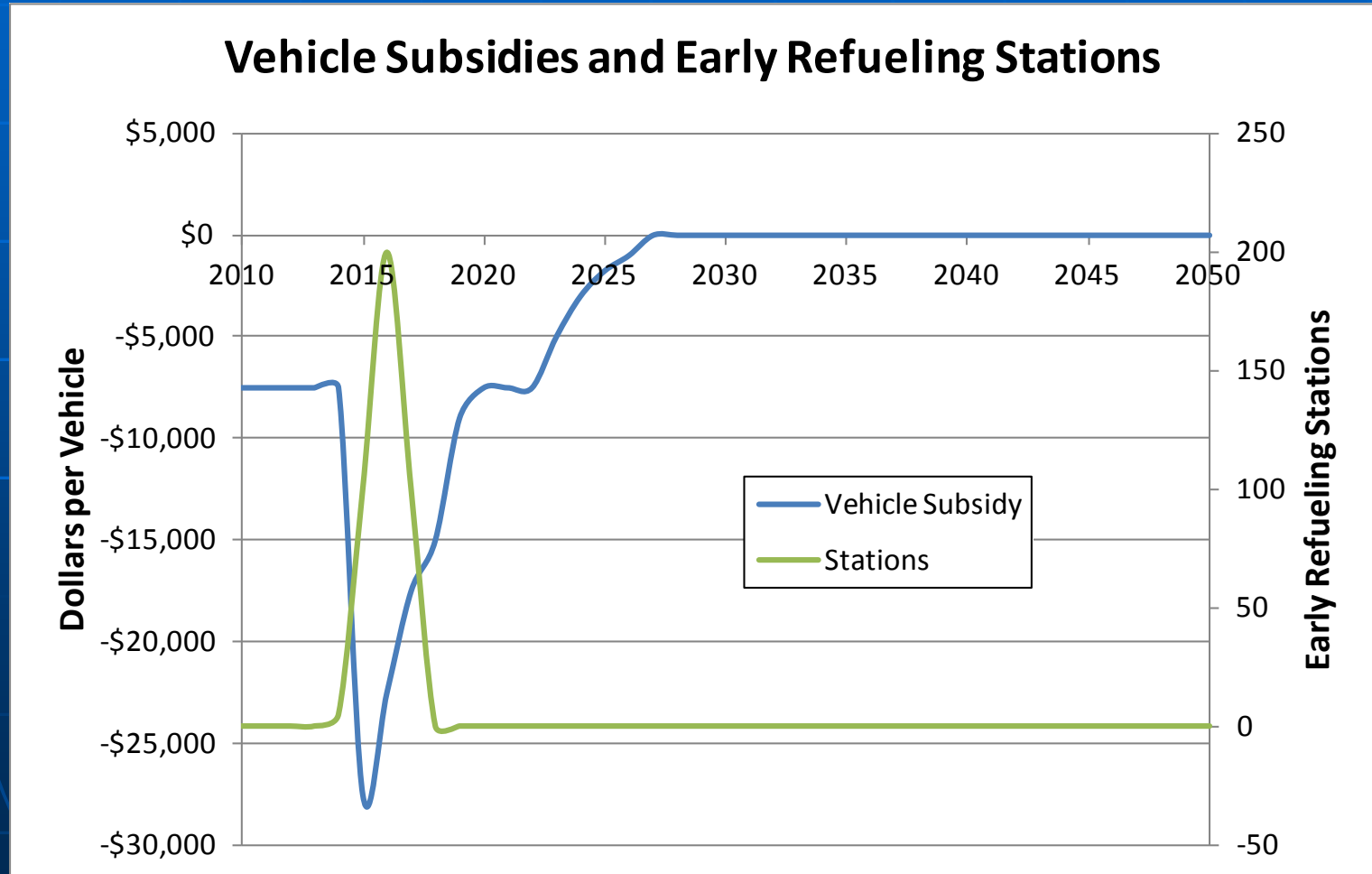




Researchers are developing models that we hope will be useful for formulating policies to accomplish the transition.

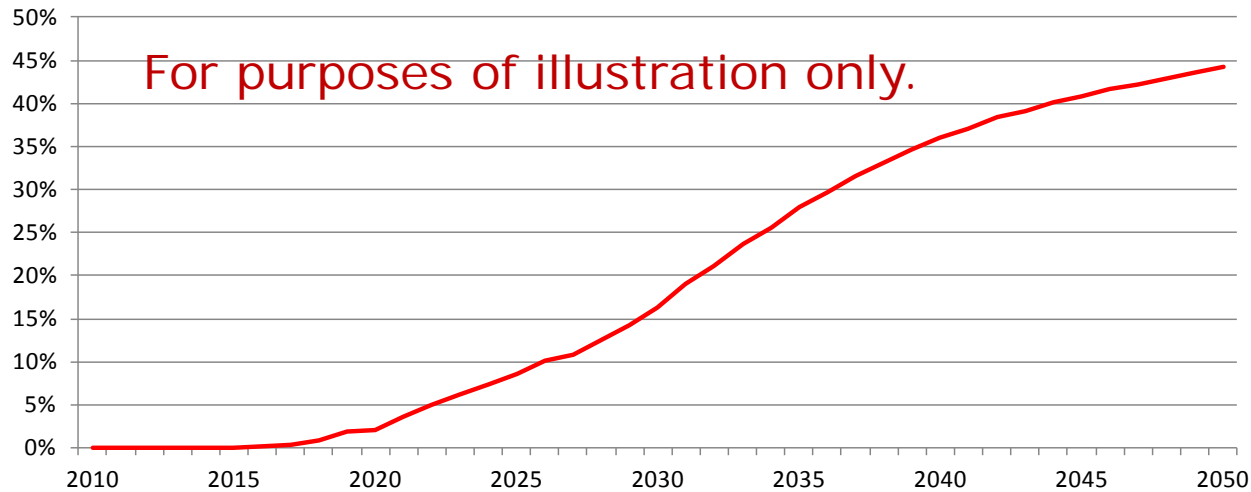


In this scenario, 5 hydrogen stations are put in service in 2014, 100 in 2015, 300 more by 2017. Mass produced fuel cell vehicles are first available to the public in 2015. Manufacturers heavily subsidize the first few vehicles sold, then the government provides a \$7,500 tax credit which is phased out by 2026.

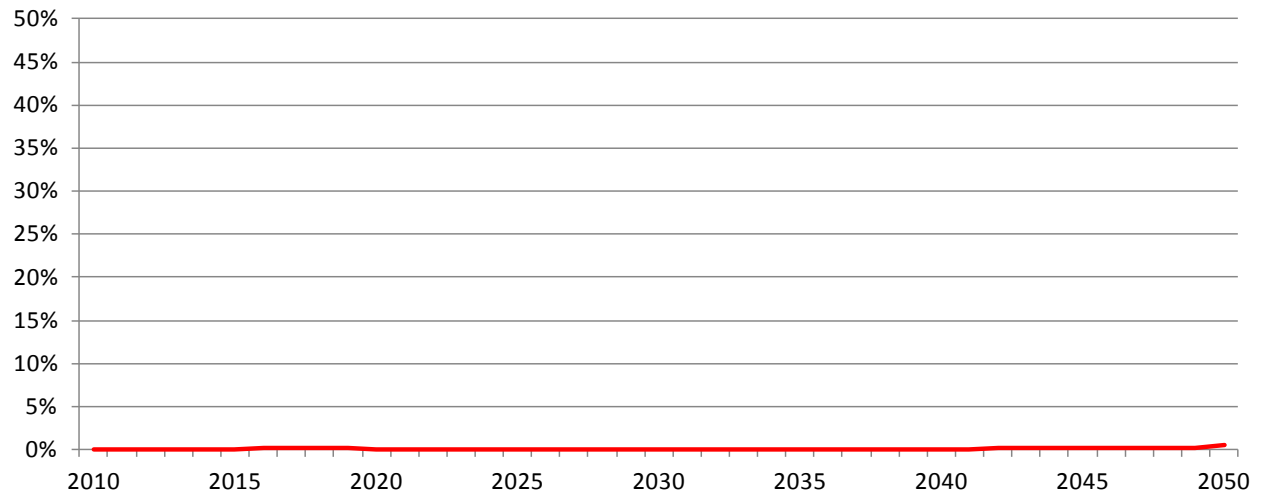


There are tipping points. Reducing the vehicle subsidy in 2016 by \$2500 or eliminating the early refueling infrastructure destroys the market! (Just a model?)

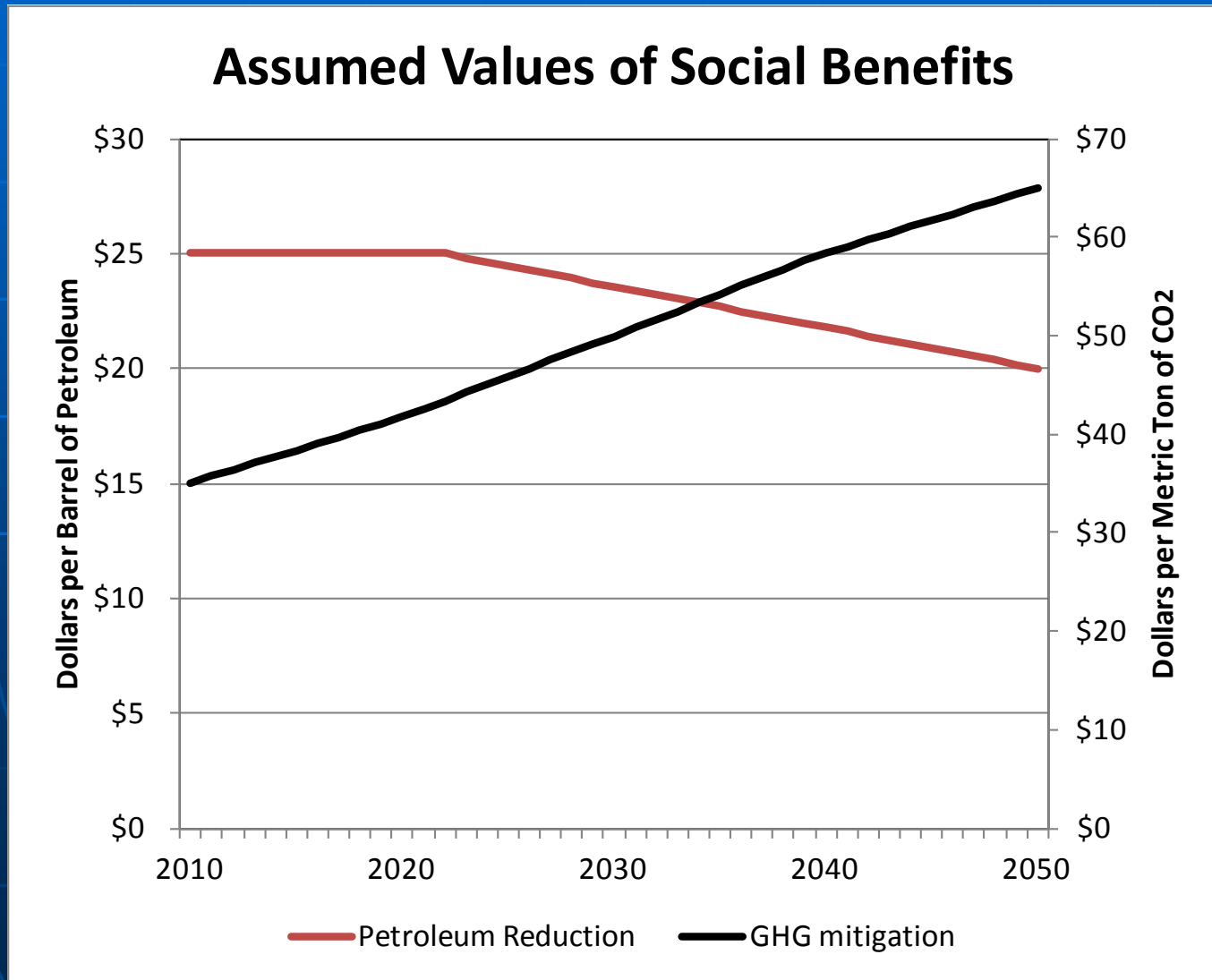
Market Shares of Hydrogen Fuel Cell Vehicles



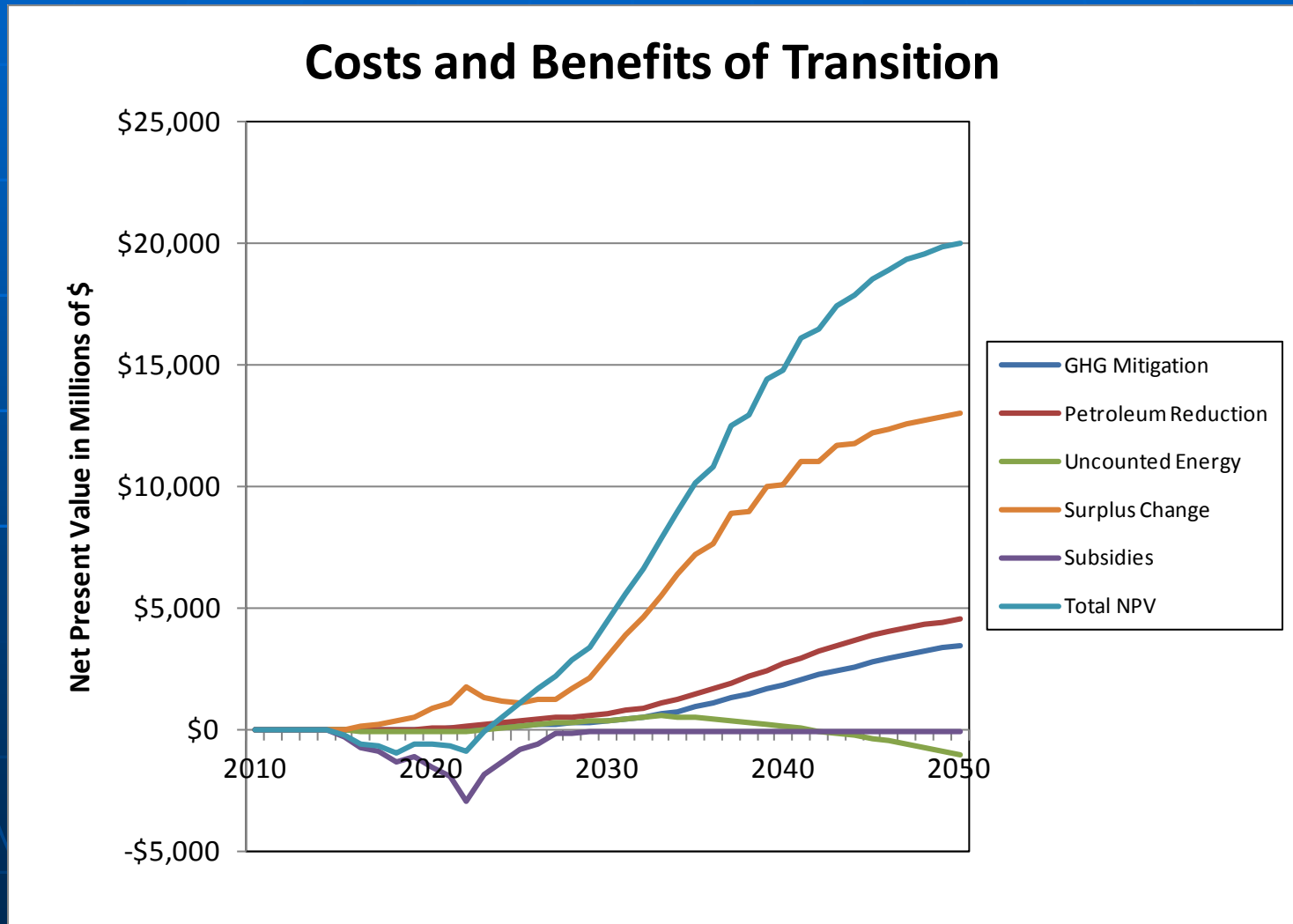
Market Shares of Hydrogen Fuel Cell Vehicles



Internalizing the external cost of carbon emissions and the social cost of oil reflected in the graph below does not induce a transition to hydrogen or plug-in electric vehicles.



Although fuel costs are no lower, FCVs are cheaper after 2040. When societal benefits are added, the transition has a NPV of \$750 billion (3% discount rate).

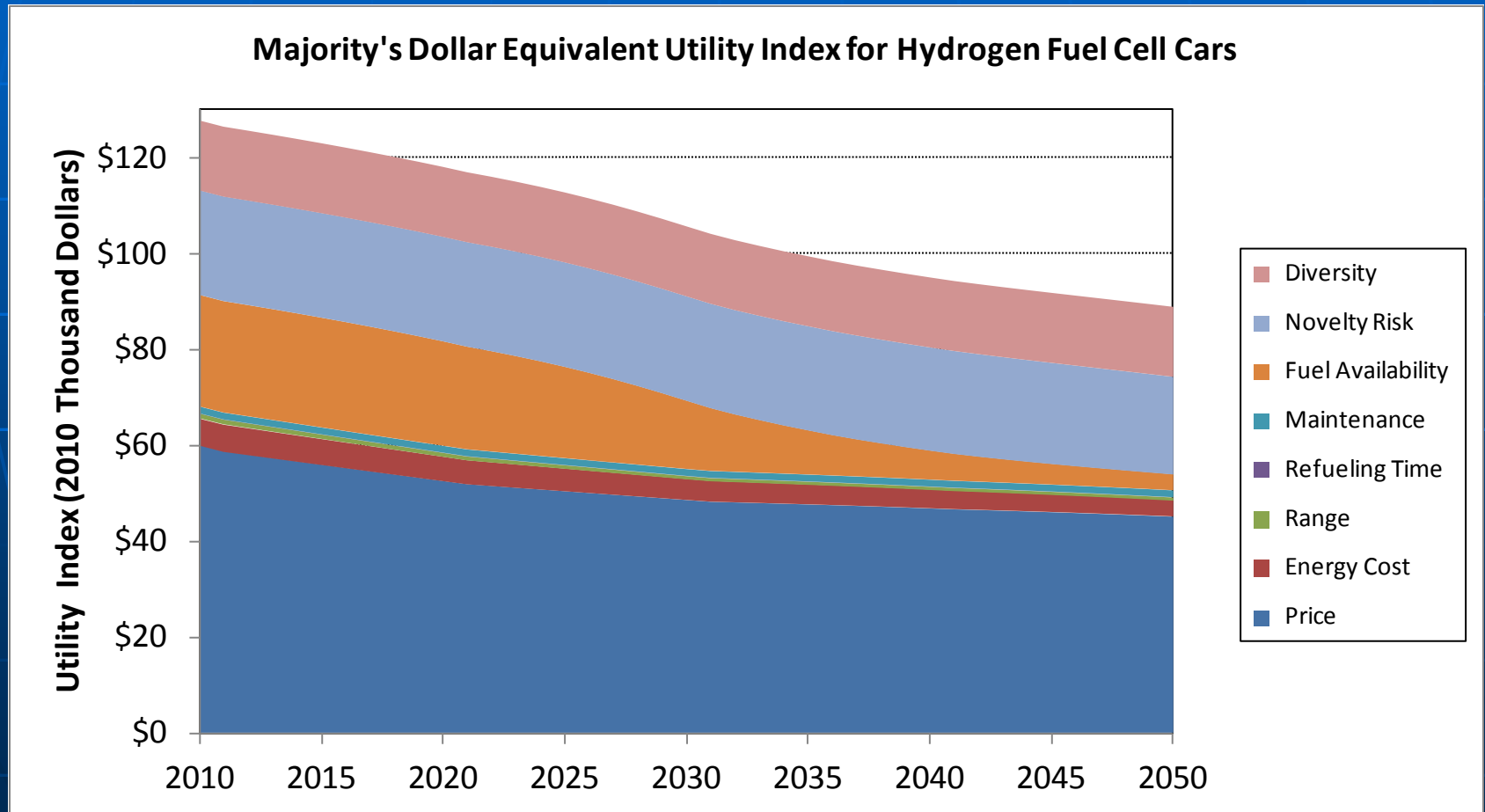


# It's a network market.

“Sequential adoption translates multiple static equilibria into the adoption dynamics characteristic of network markets: *early instability and later lock-in*.” (Farrell and Klemperer, 2007, p. 1975)

- Looked at another way, the reductions in transition costs created by early adopters and government policies become external benefits.
  - Learning by doing
  - Scale economies
  - Diversity of choice
  - Learning on demand side (early adopter, etc.)
  - Chicken or egg (fuel availability)
- Another refueling/recharging station produces indirect external benefits for vehicle owners.
- Another vehicle on the road makes alternative fuels stations more profitable.
- There are positive feedbacks, multiple optima and tipping points.

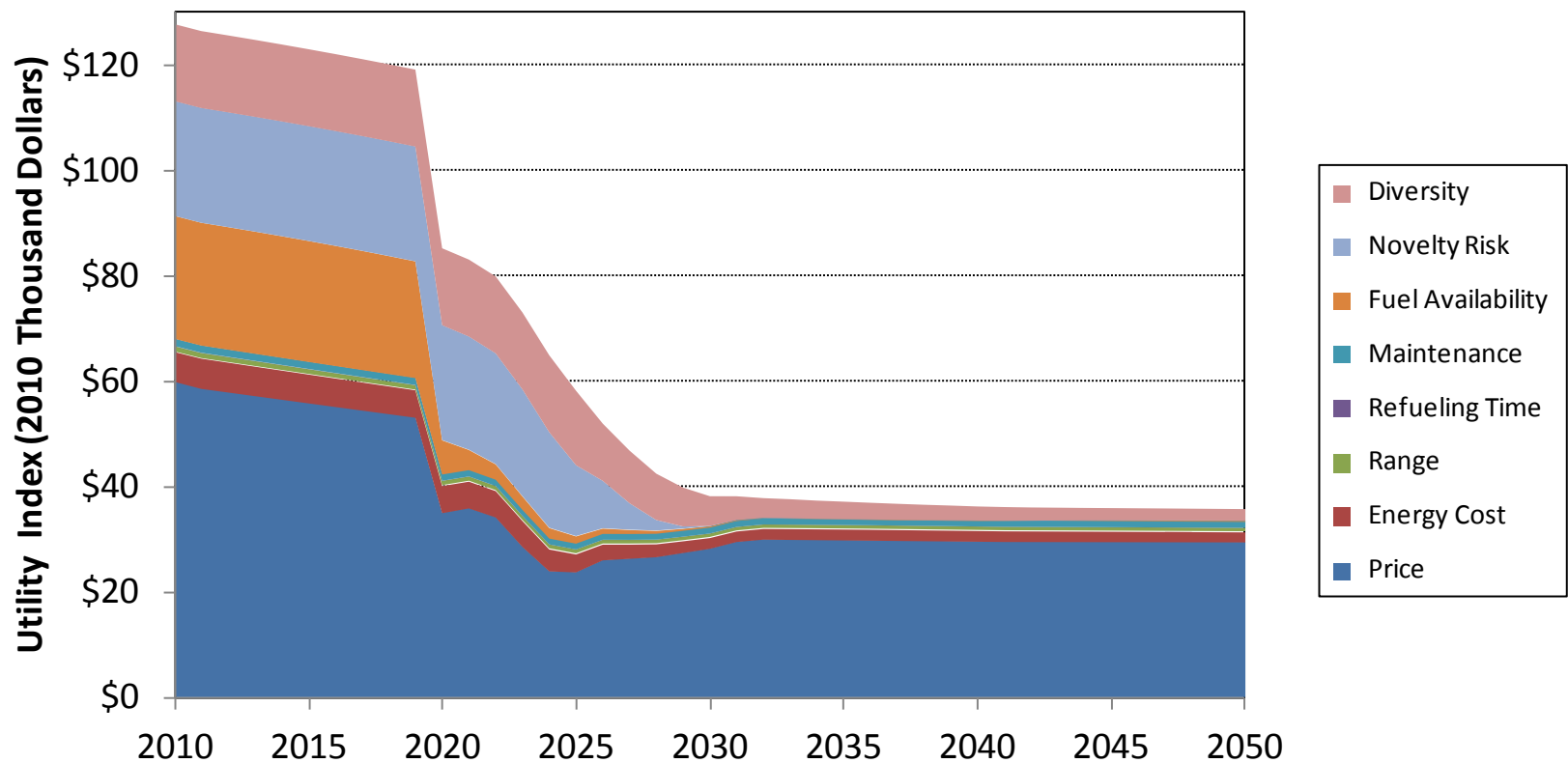
Without any market interventions to break down the transition barriers costs decline over time, mostly due to technological progress, but not nearly enough.



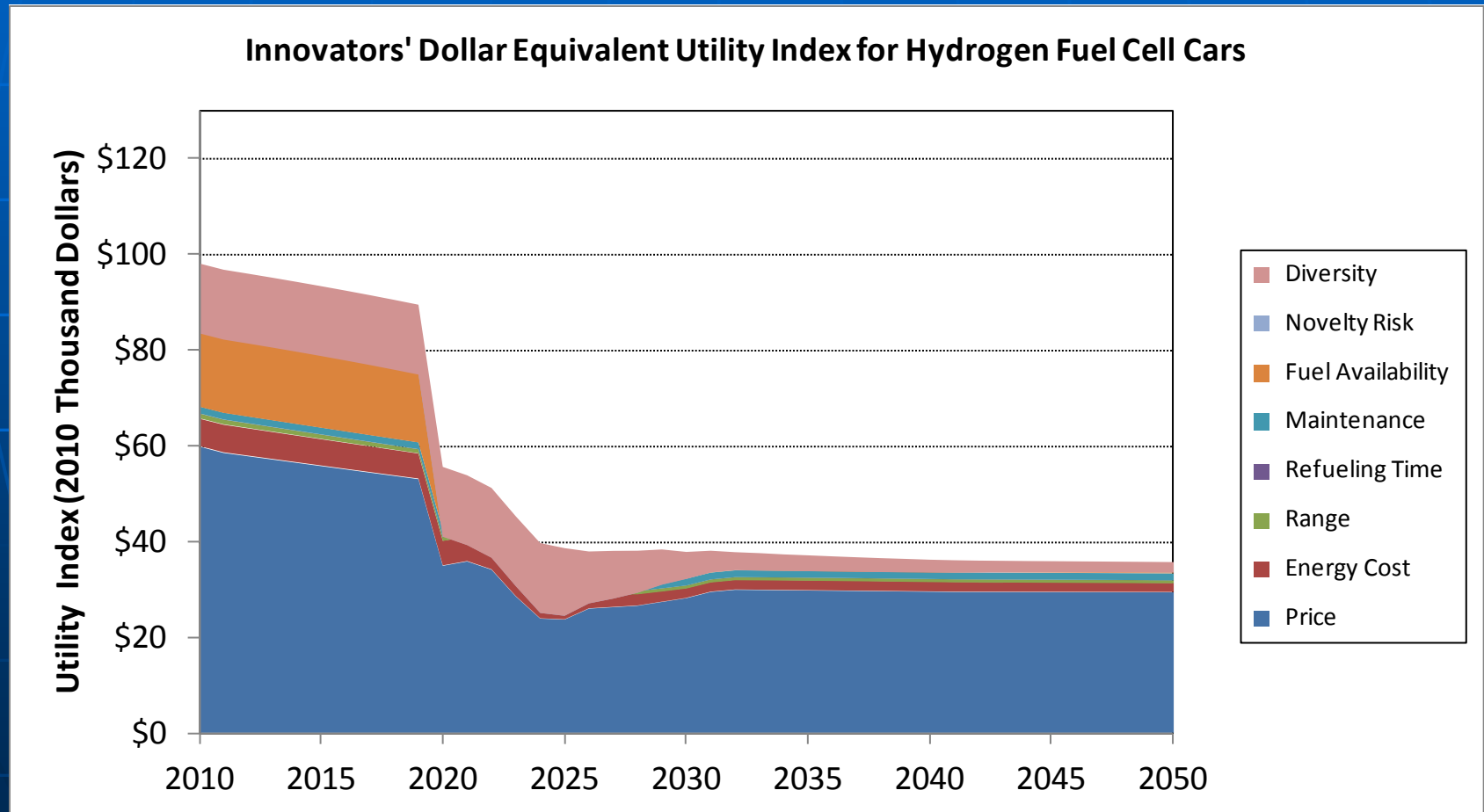


Pre-installation of refueling infrastructure and vehicle subsidies are effective even though majority consumers' risk aversion, lack of diversity in vehicle choices, and higher fuel costs must still be overcome.

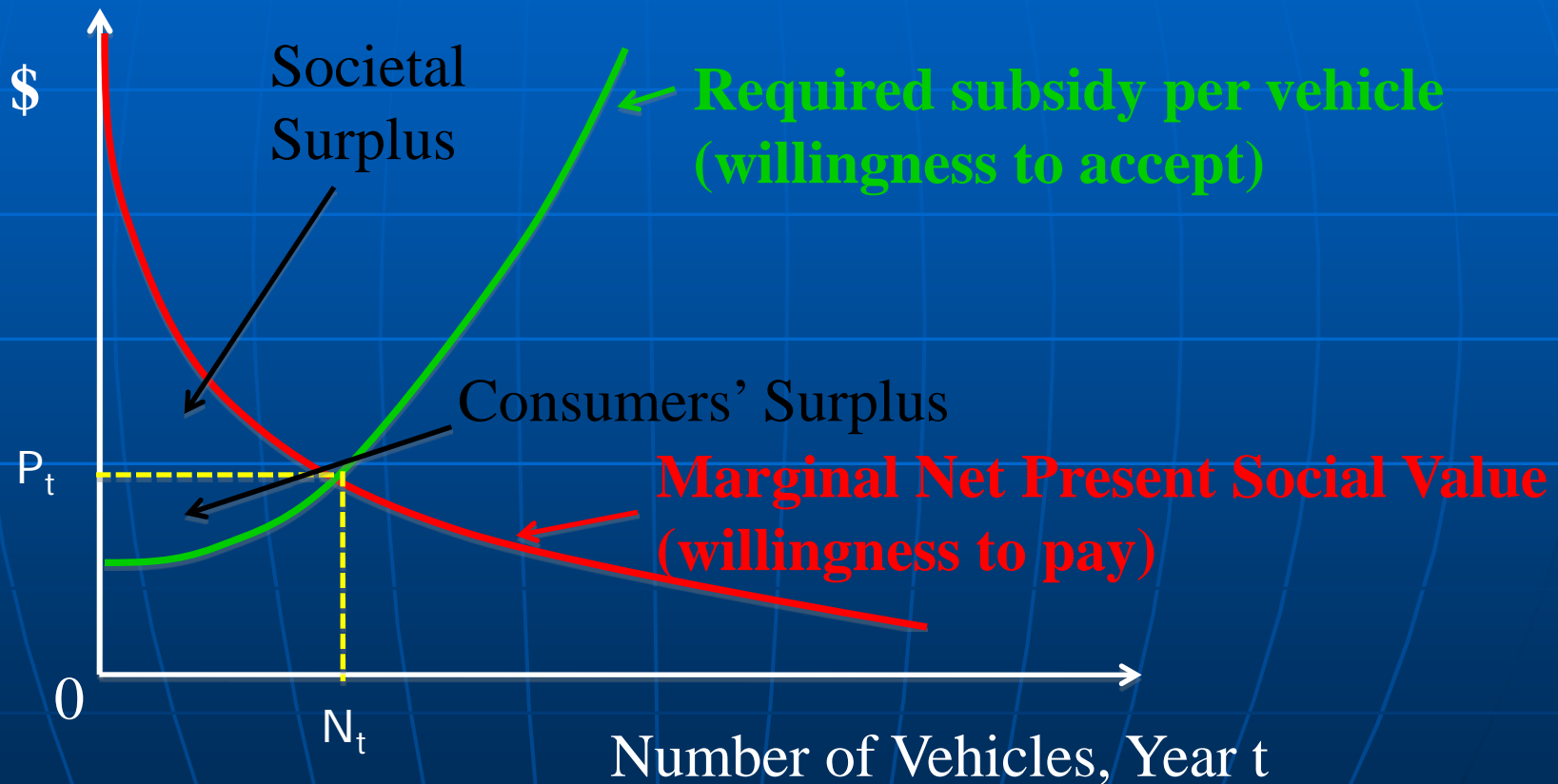
Majority's Dollar Equivalent Utility Index for Hydrogen Fuel Cell Cars



The innovators and early adopters drive the early market, creating network external benefits for subsequent adopters.



In year  $t$ , there is a social willingness to pay for having more vehicles in operation ( $dNPV/dN$ ) and a market willingness to accept a vehicle ( $dN/dP$ ). There is an equilibrium price that provides “surplus” to both and results in sales of  $N_t$  vehicles at a subsidy of  $P_t$ .



Very likely we need a new public policy paradigm for dealing with such a large-scale energy transition under deep uncertainty.

- Maximize expected risk-weighted NPV
- Pursue N paths with likely failures
  - Is the public ready for this?
- Learn by doing, researching, & modeling
  - Revise estimated "buy down" costs (network externalities) and social values
  - Find new "efficient" paths
    - Social willingness to pay
    - Private willingness to accept



Thank you.

# What can we learn from such analytical tools?

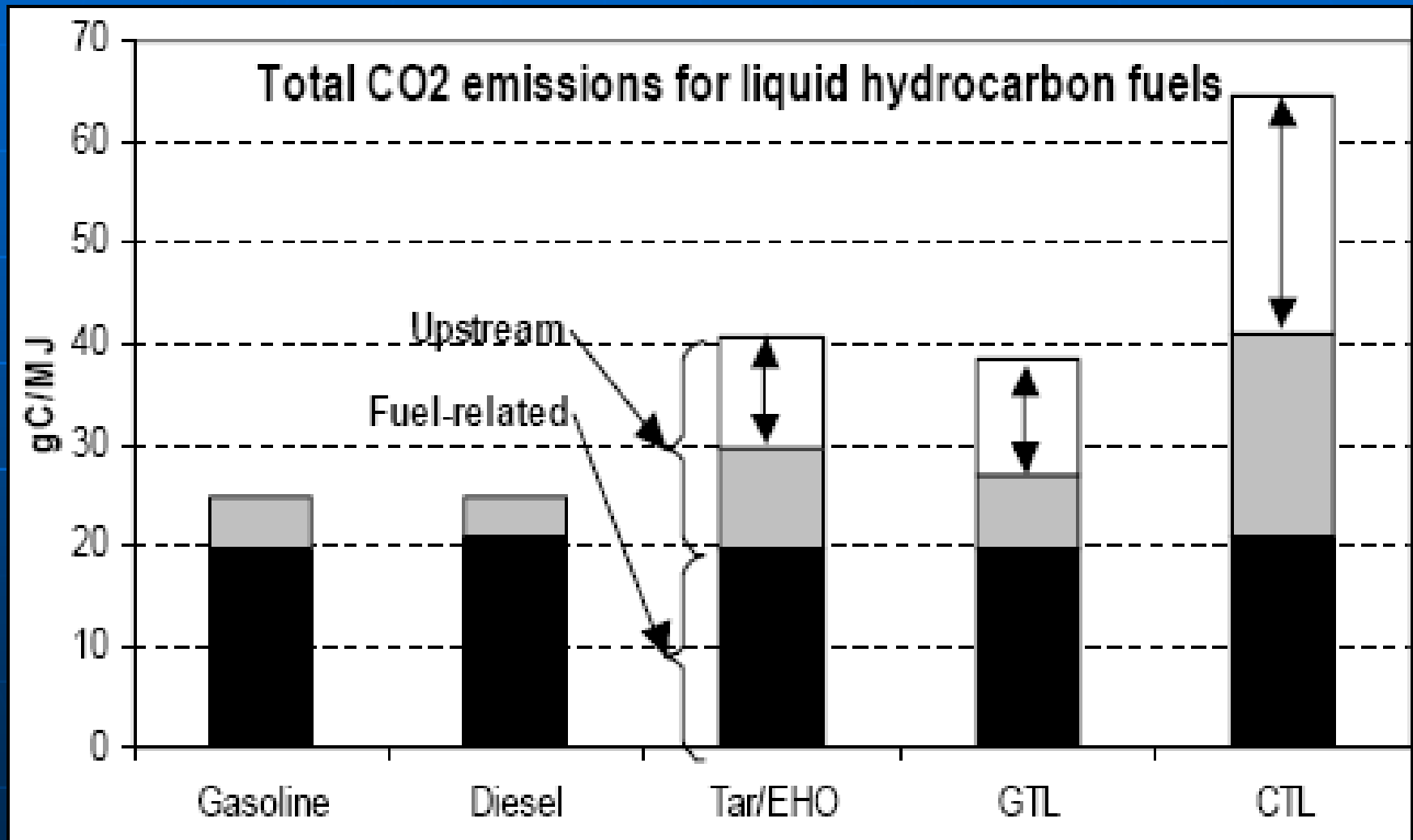
- What must we learn about transition barriers and policies, both in theory and empirically?
- Time constants for change.
- Quantification of potential costs and benefits.
- Critical linkages to other systems
- Insights about technological goals.
- Insights about key uncertainties.
- Insights about the role of public policies.
- Envisioning the transition.
- Developing a paradigm (theory, model) for a rational transition.
- Understanding important vulnerabilities.
- Developing robust, efficient policy choices.



# BIG QUESTIONS:

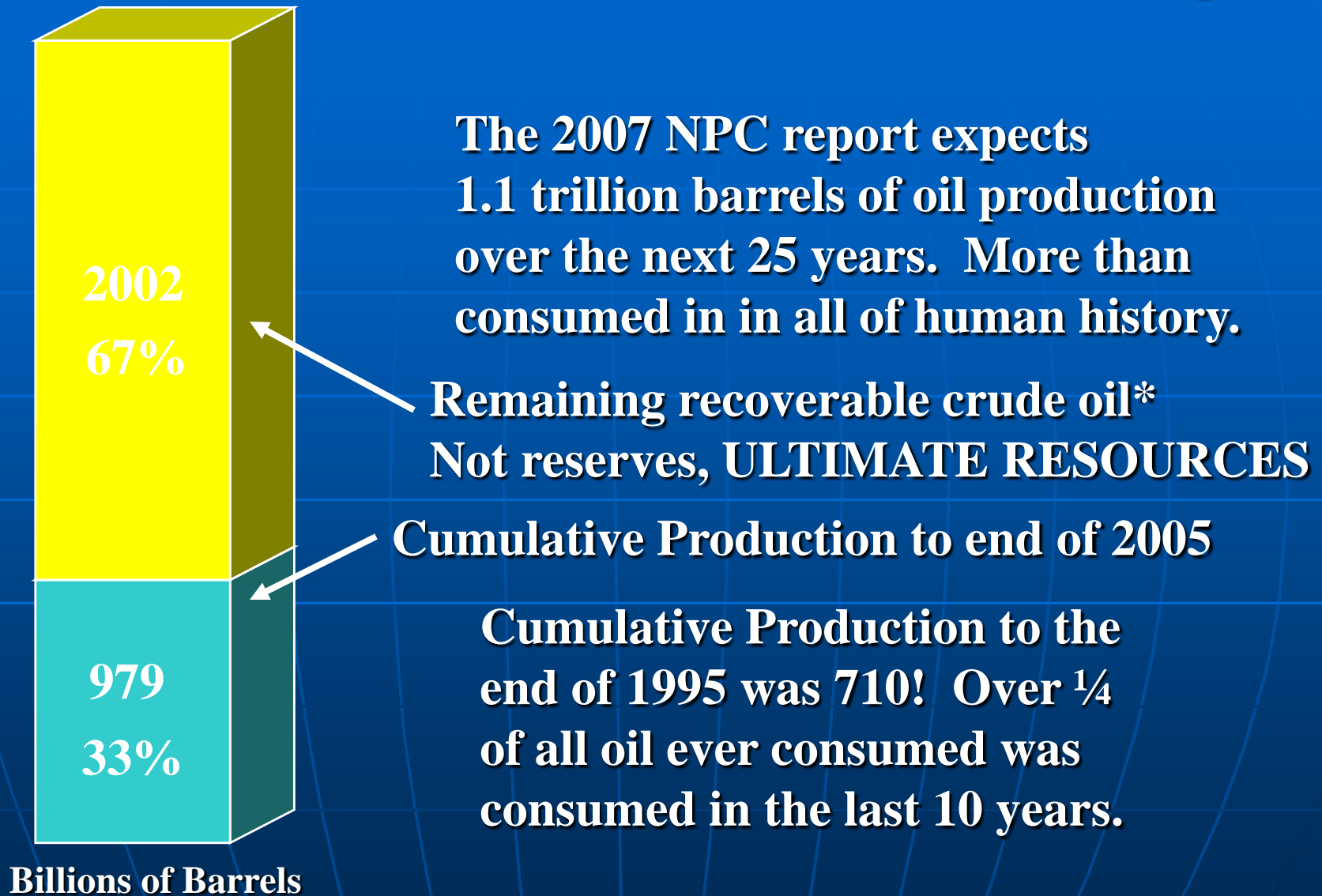
- How can we accomplish large-scale energy transitions for the public good?
  - What are the robust, efficient strategies & policies?
  - How can we cope with technology & market uncertainties?
- How much can we reduce uncertainty about key parameters and processes?
- Can we measure and monitor global energy sustainability? (e.g., Graedel & Van der Voet, 2011, *Linkages of Sustainability*, MIT Press)

GHG emissions from oil sands are 20% to 80% higher than gasoline from conventional oil and liquid fuels from coal (CTL) would likely more than double CO<sub>2</sub> emissions (without Carbon Capture & Storage).



Source: Farrell, 2006.

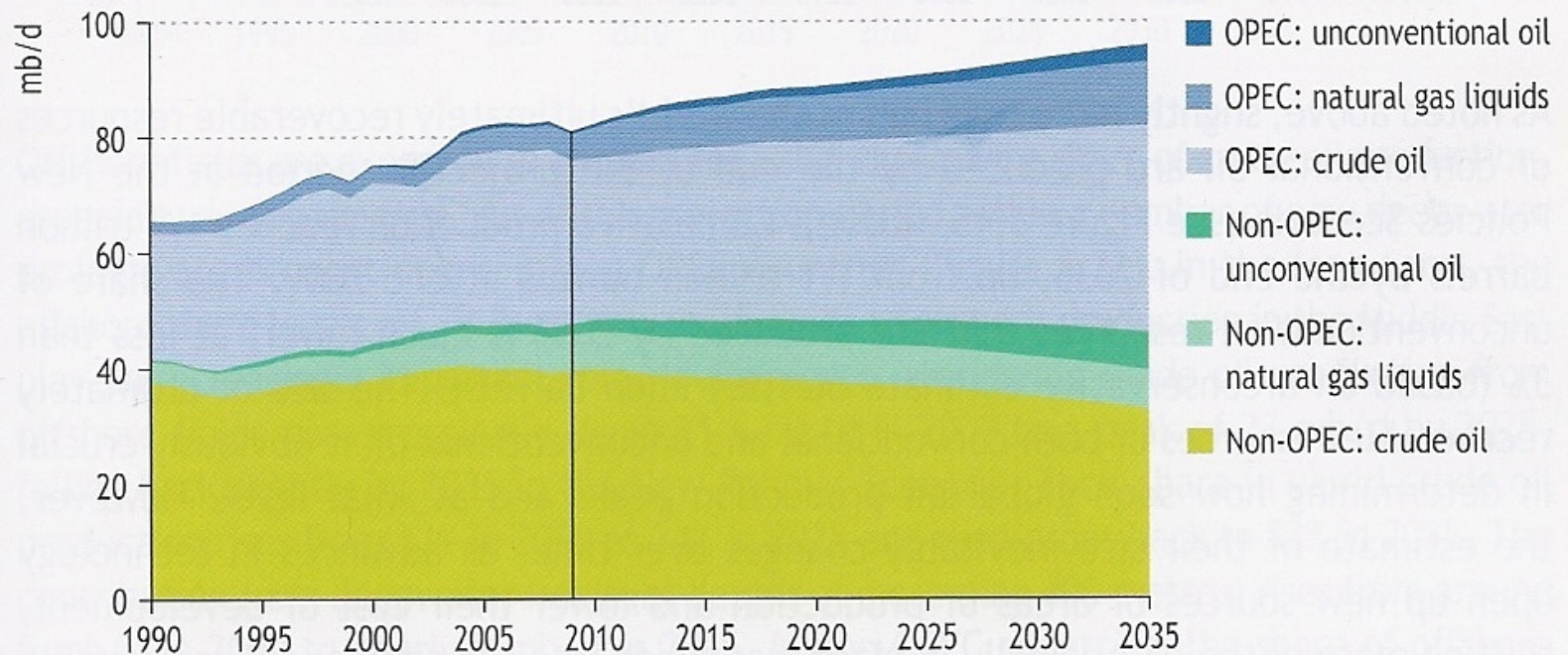
# The RATE of world oil use is alarming!



\* From USGS 2000, USGS 1995, and MMS 1996

The International Energy Agency foresees a plateau in non-OPEC conventional **and** unconventional oil production from now to 2030. So does BP and ExxonMobil.

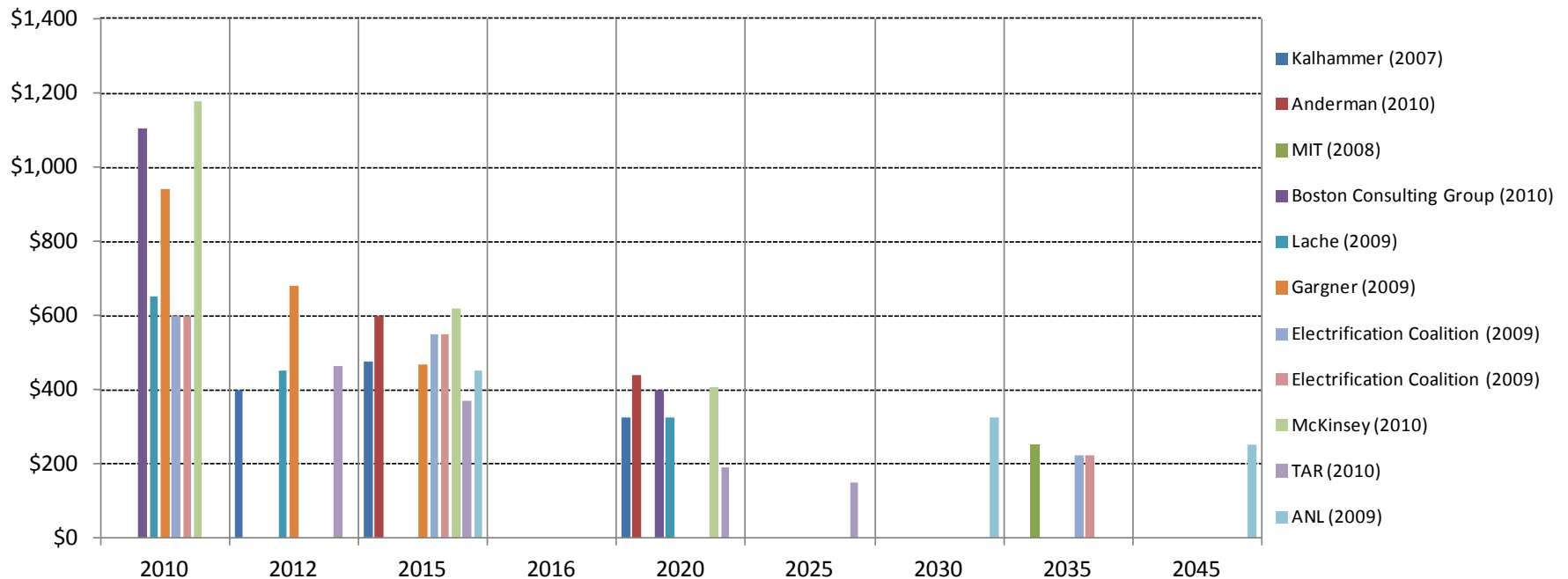
**Figure 3.18** • World oil production by source in the New Policies Scenario



Source: International Energy Agency, *World Energy Outlook 2010*, OECD, Paris.

There is a general expectation of significantly declining battery costs but when costs might fall to \$200/kWh or less is very important to current policy actions.

**Battery Cost Estimates for BEVs (\$/kWh nominal capacity)**



# Carbon Reservoirs

Atmosphere 800 GtC (2004)

Biomass  
~500 GtC

Soils  
~1,500 GtC

N. Gas  
~260 GtC

Oil  
~270 GtC

Coal  
5,000 to 8,000 GtC

Source: Edmonds, 2005

Unconventional Fossil Fuels  
15,000 to 40,000 GtC



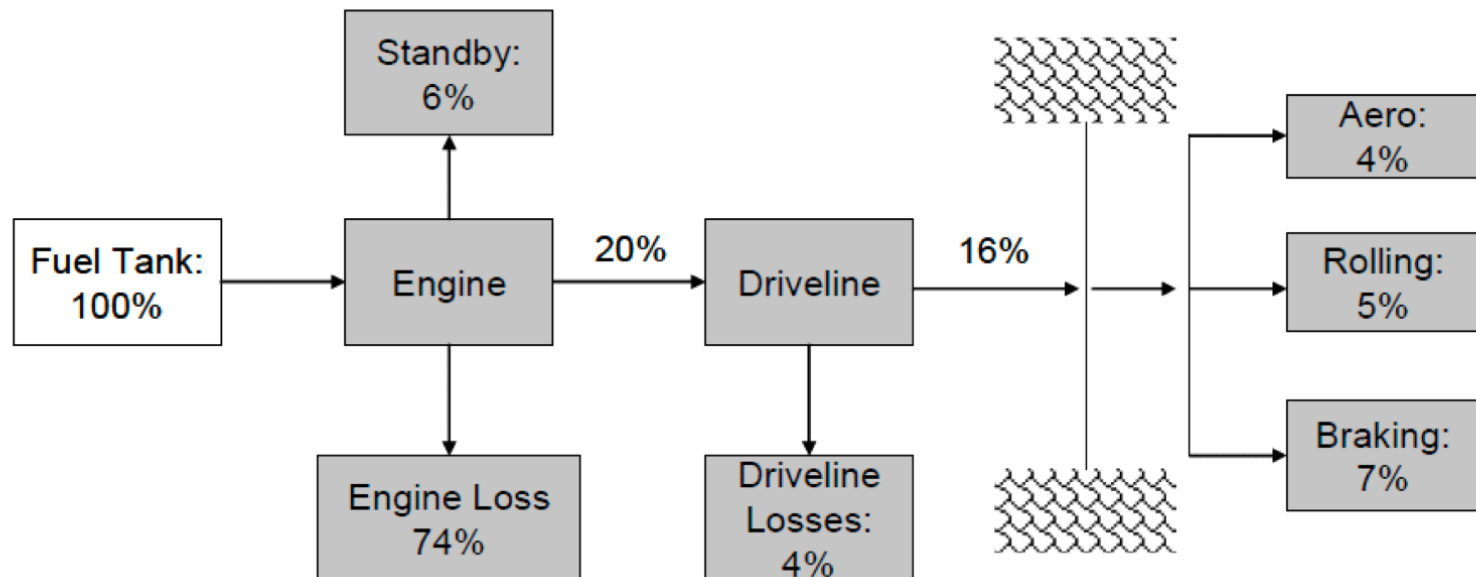
Step 1: Is the societal goal worth achieving.

- ❖ In terms of the *net present value* of the transition:
  - ❖ Private benefits  $<$  Private costs ?
    - ❖ Short run: Yes, because of transition barriers and external costs of current system.
    - ❖ Long run: Uncertain
  - ❖ Public goods benefits  $>$  Transition + Long run private costs ?
  - ❖ Is the net present societal value of transition  $>$  net present societal value of no transition?
- ❖ What about uncertainty of technological progress?



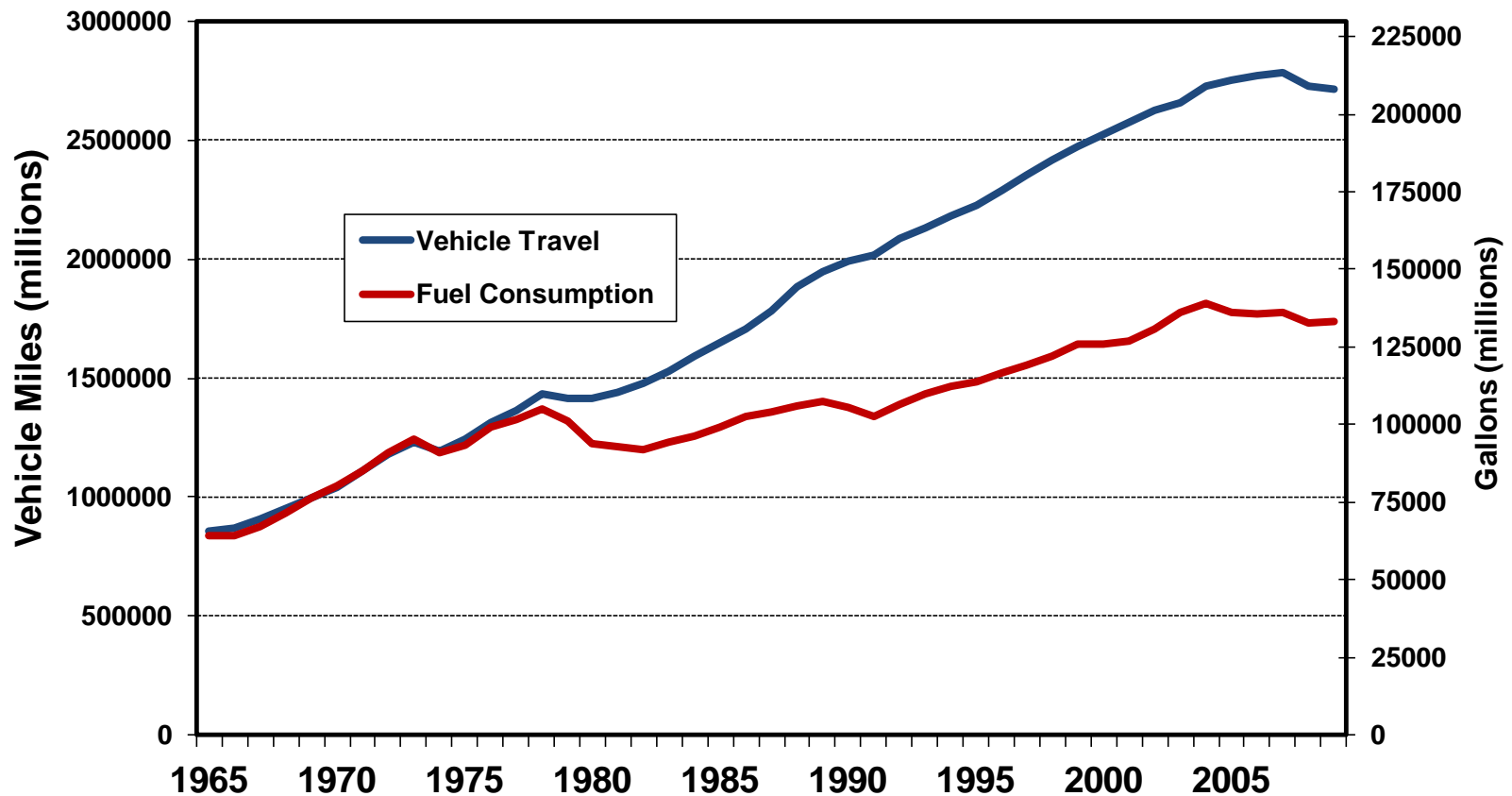
The overall energy efficiency of U.S. passenger vehicles is  $\approx 1\%$ .  
Fuel to wheels  $\sim 16\%$ , “payload”  $\sim 1/16^{\text{th}}$  of total mass.

Though this is an extreme example, it is reasonable to infer potential for major improvement.



The CAFE standards, passed in late 1975 decoupled vehicle travel and fuel consumption, saving about 70 billion gallons of fuel/year.  
The public *likes* the fuel economy standards.

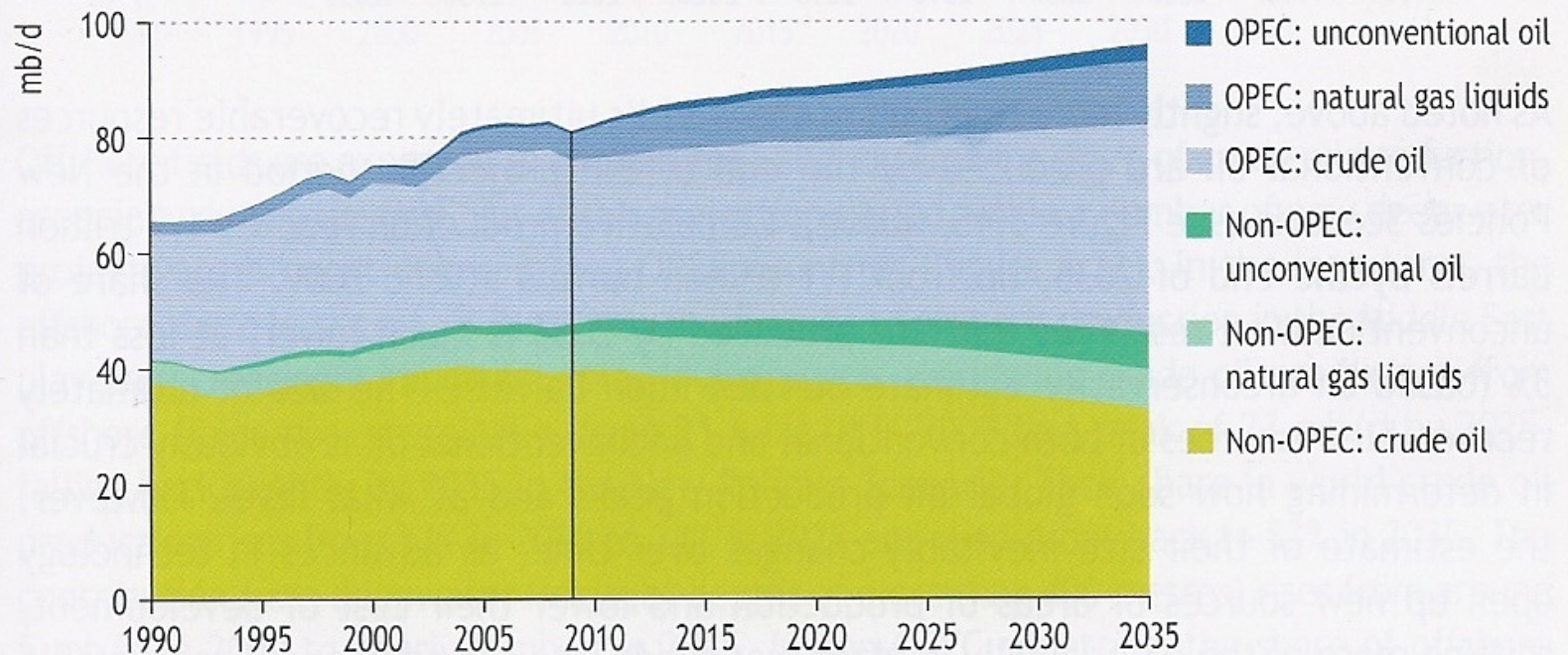
Miles of Travel and Fuel Use by Light-duty Vehicles: 1965-2009



U.S. Dept. of Transportation, Federal Highway Administration, Highway Statistics, table VM-1.

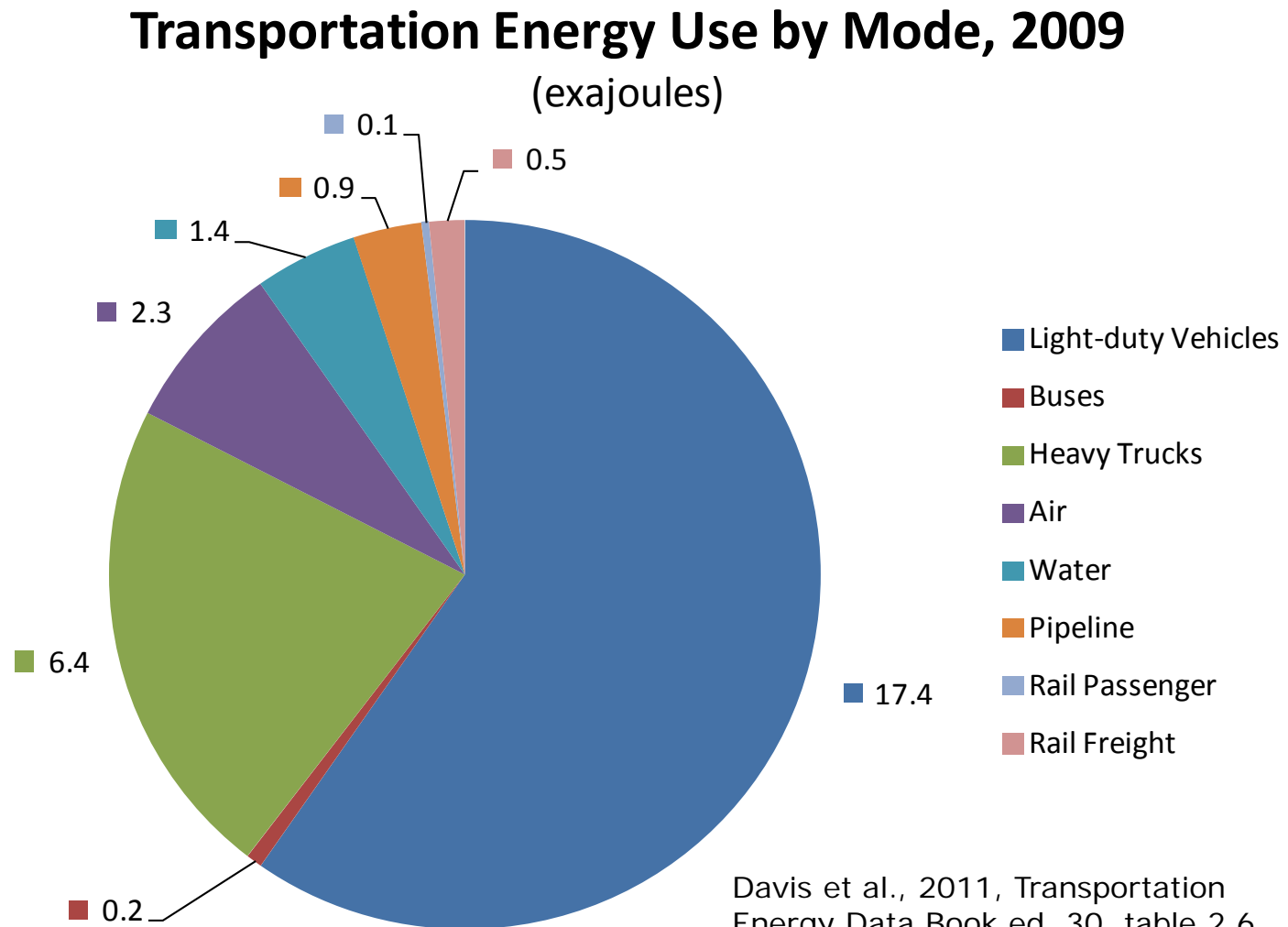
The International Energy Agency foresees a plateau in non-OPEC conventional **and** unconventional oil production from now to 2030. So does BP and ExxonMobil.

**Figure 3.18** • World oil production by source in the New Policies Scenario



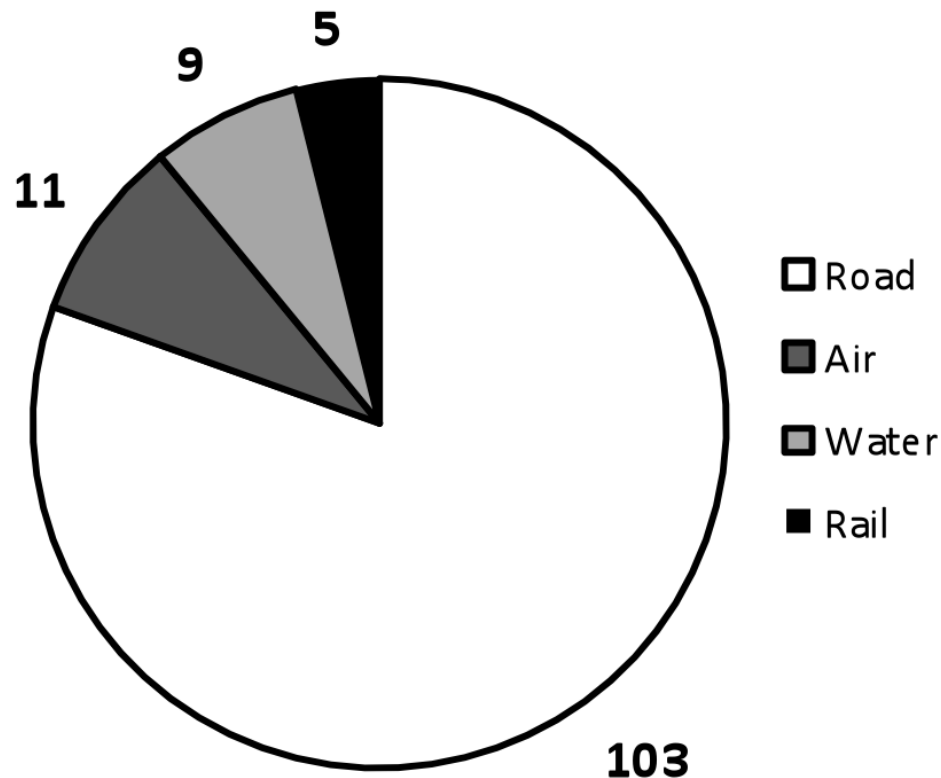
Source: International Energy Agency, *World Energy Outlook 2010*, OECD, Paris.

# Today we are focused on passenger cars and light trucks.



Petroleum provides 95% of the energy for global transport, which produces 15% of global anthropogenic GHG emissions. Transport energy use is expected to approximately double by 2050 under BAU.

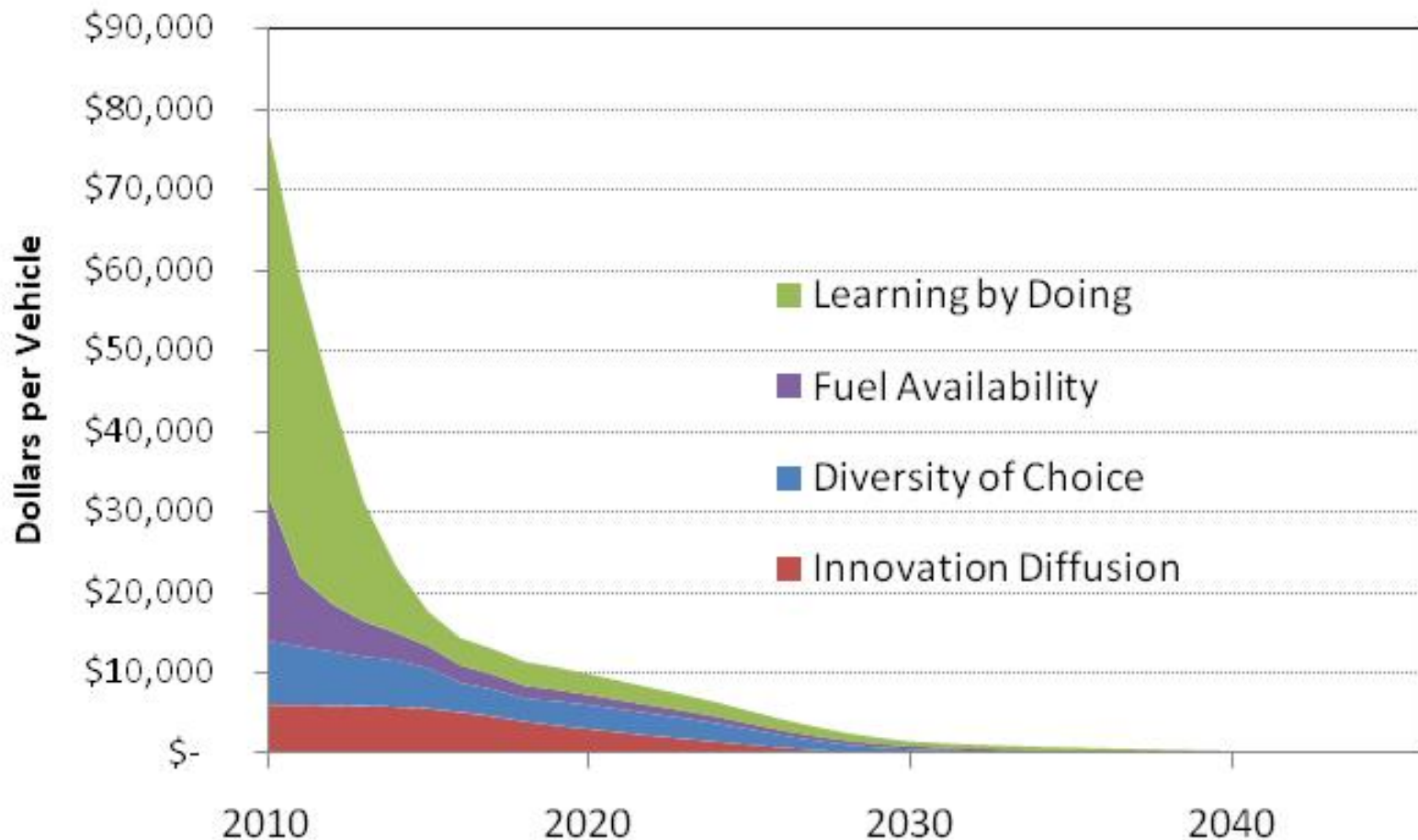
**Global Transport Energy Use by Mode, 2007  
(exajoules)**



**The “buy down” approach hypothesizes that paying the “excess costs” of the transition would be effective and efficient.  
But would it?**

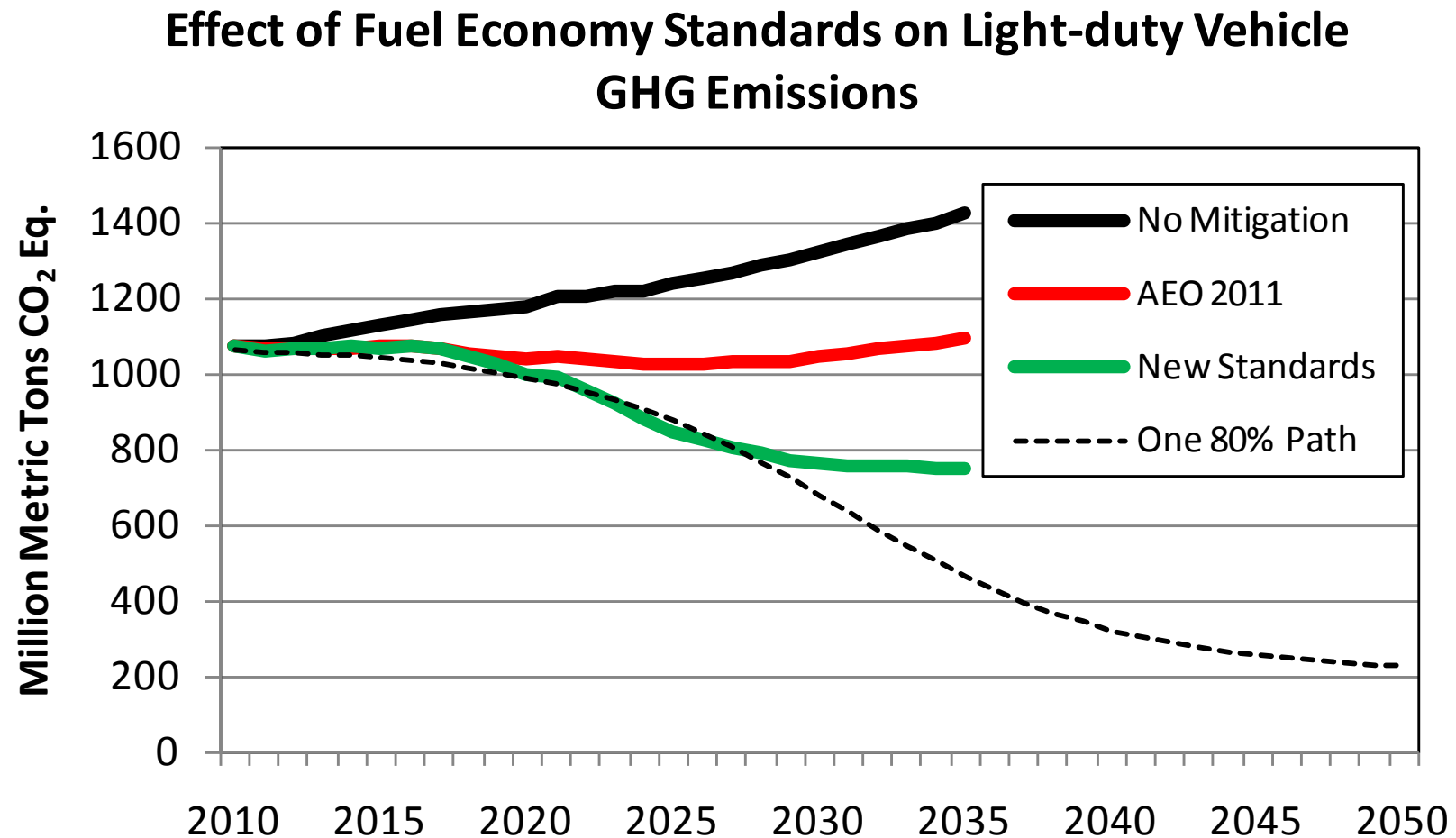
“Buy-down” cost estimates:

Calculation for Fuel Cell Vehicles



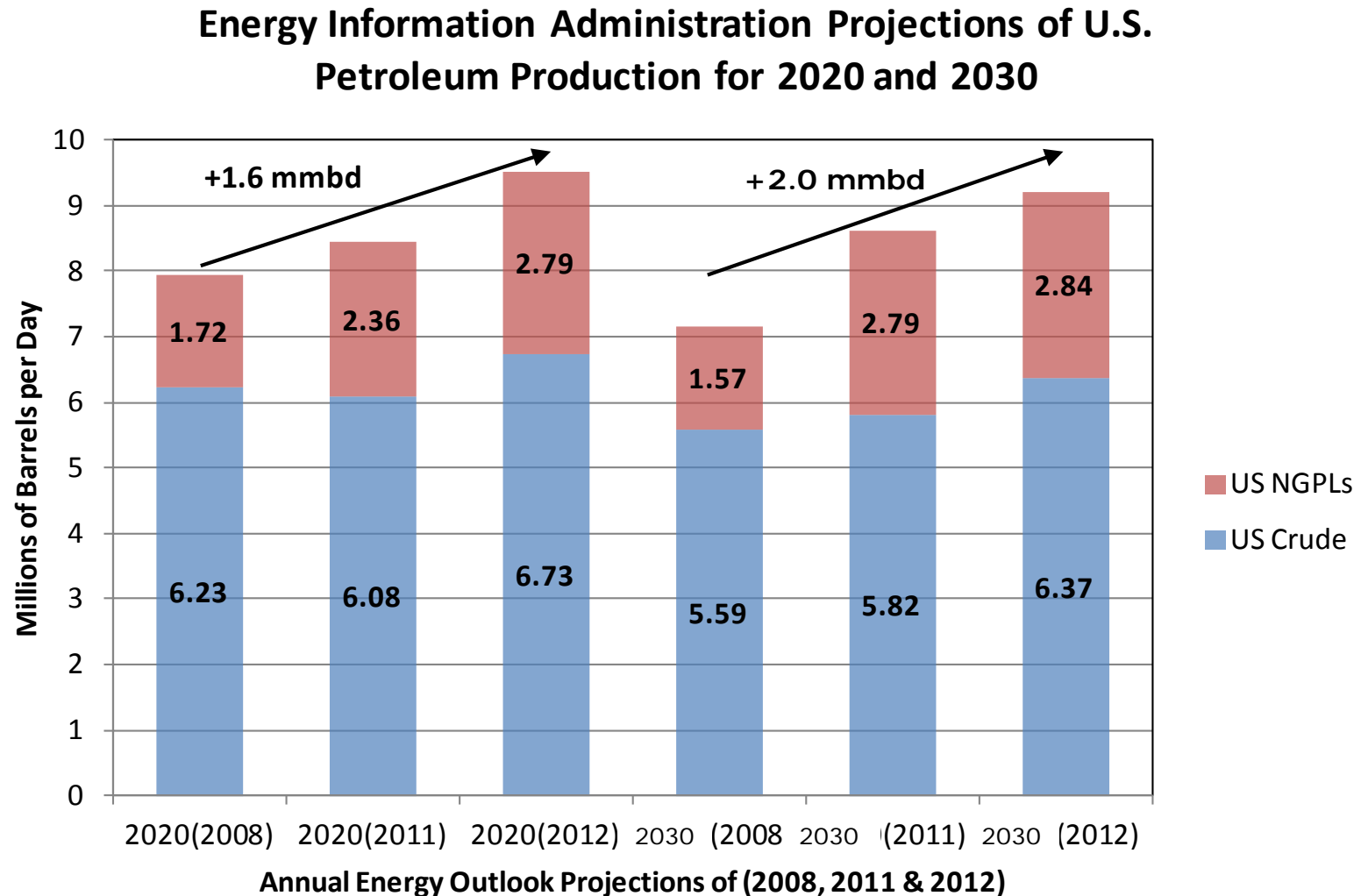


**USE LESS OIL:** The proposed 2017-2025 US standards appear to put light-duty vehicles on a path toward an 80% reduction in CO<sub>2</sub> emissions through 2025.





**PRODUCE MORE OIL:** Increased domestic production of shale oil and NGPLs are expected to add 1.6 mmbd by 2020 and 2.0 mmbd by 2030 vs. projections of just four years ago.



The reduction in GHG emissions versus 2005 is over 60%.

