# Comparison of Plug-in Hybrids, Fuel Cell EVs and Battery EVs

Presented to the
Hydrogen Technical Advisory Committee
Windsor, Connecticut

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# Topics

- Review National Hydrogen Association "Energy Evolution" Model
- Compare Fuel Cells with Batteries
- Government Incentives Required to Jump-Start FCEVs, PHEVs and BEVs

# NHA "Energy Evolution" Task Force Participating Organizations

## Task Leader: Frank Novachek (Xcel Energy)

- ARES Corp.
- BP
- Canadian Hydrogen Energy Company
- General Atomics
- General Motors
- H2Gen Innovations
- ISE Corporation
- National Renewable Energy Laboratory
- Plug Power, LLC
- Praxair
- Sentech
- University of Montana
- Shell Hydrogen
- Xcel Energy

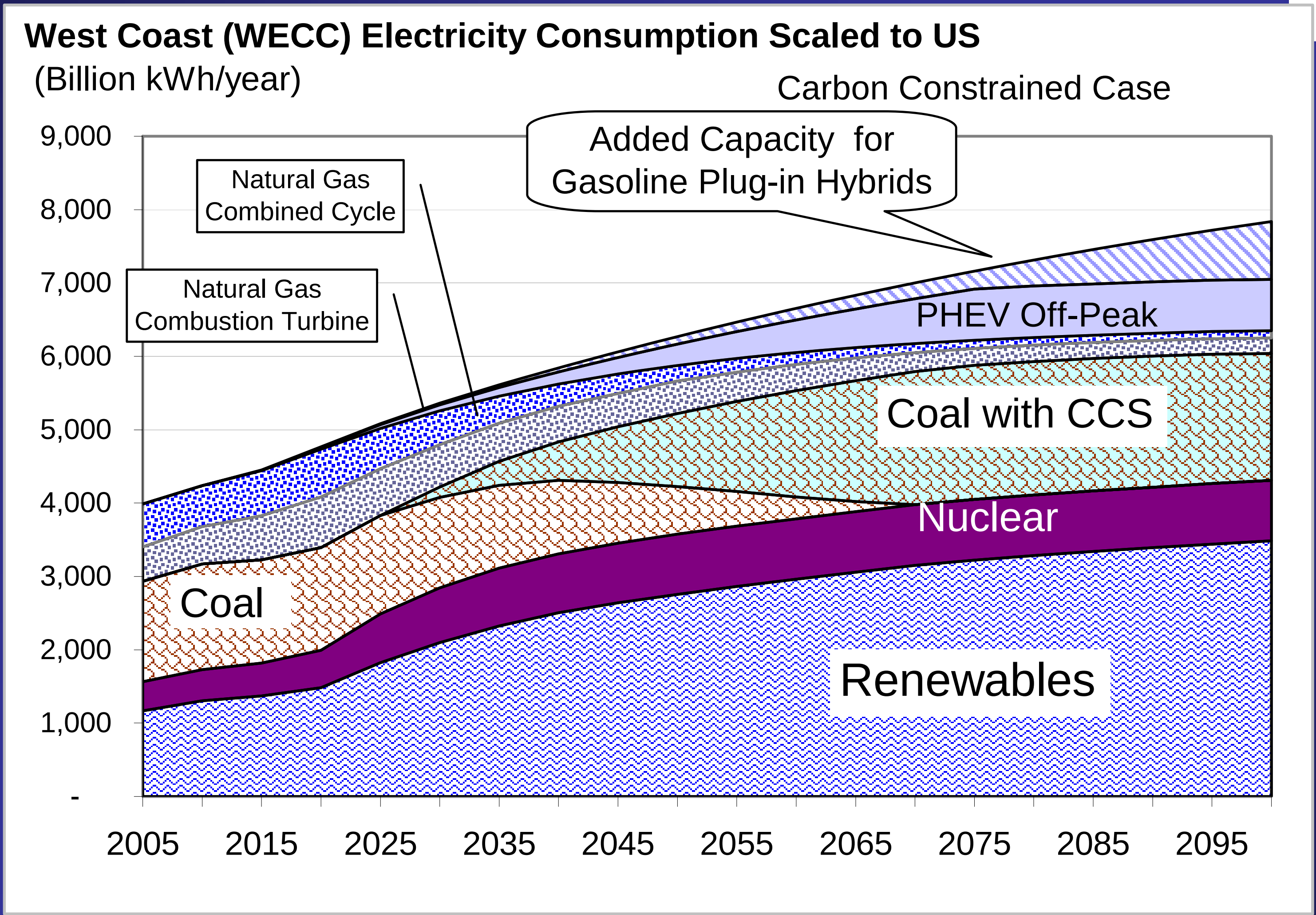
## NHA Disclaimer:

"This consensus presentation does not necessarily represent the organizational views or individual commitments of all members of the National Hydrogen Association."

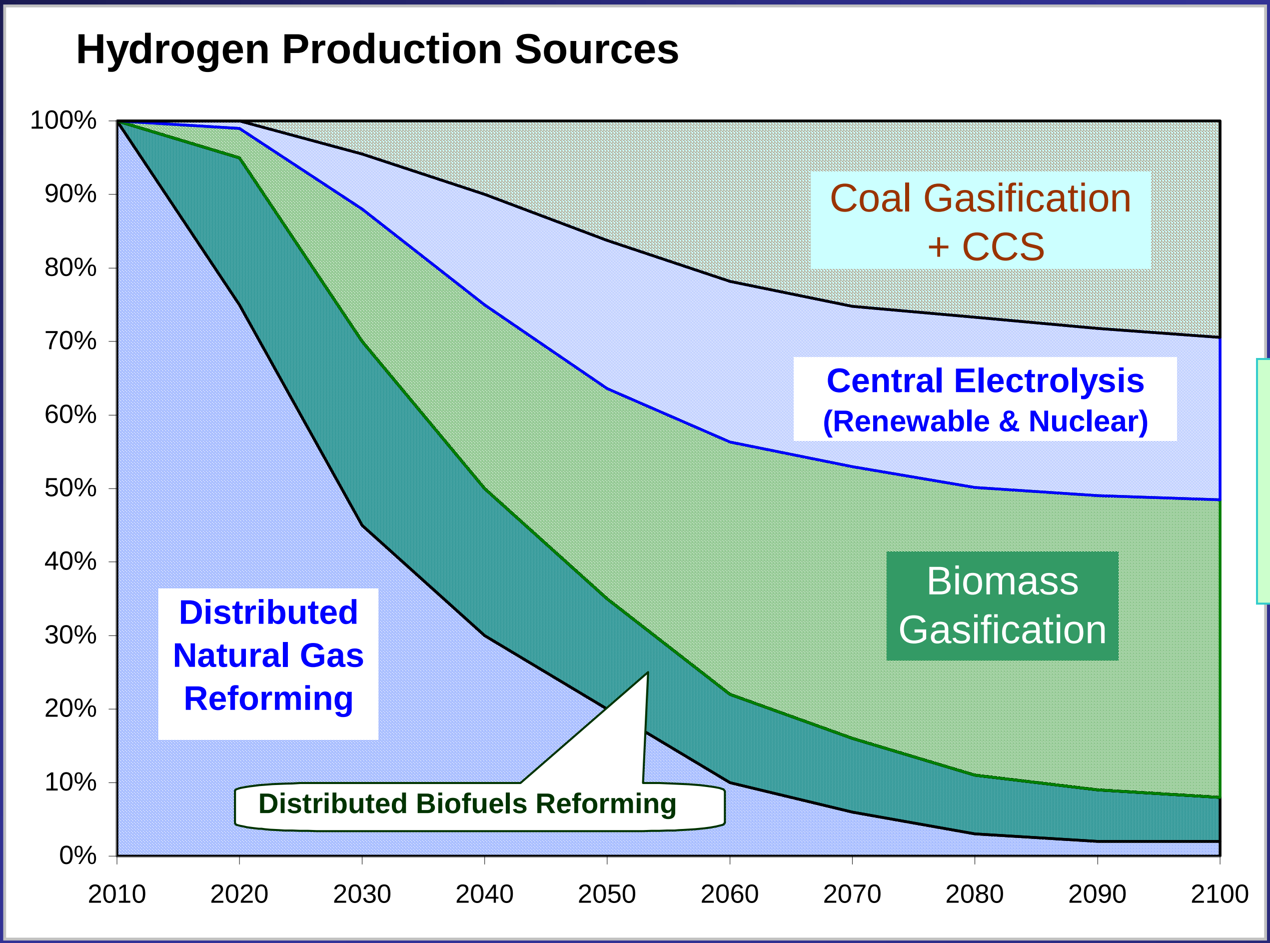
# Key Assumptions

- Assume success for all options
  - Technical success
  - Vehicles are affordable
- Assume stringent climate change constraints
  - Hydrogen production becomes green over time
  - Electricity production becomes green over time

# Greening of Electrical Grid



# Greening of Hydrogen Production




CCS = carbon capture and storage

Assumes that coal with CCS & biomass will dominate long-term central hydrogen production (Similar to NRC 2008)

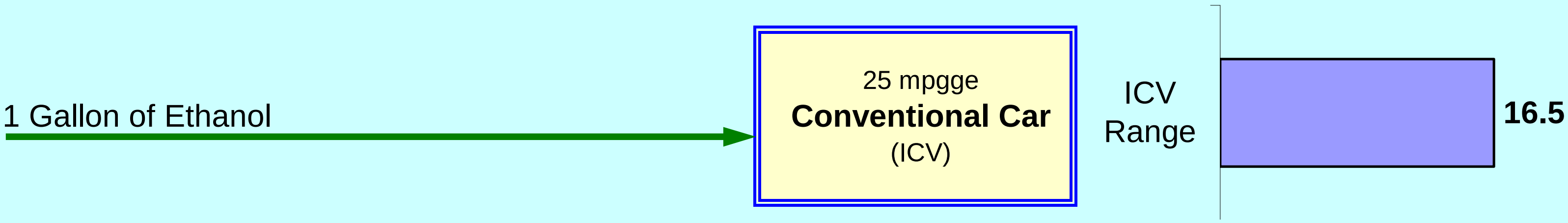
Summary Greet 1.8a.XLS; Tab 'Fuel TS'; N 97 3/1 /2009

| | 2020 | 2030 | 2050 | 2070 | 2100 |
|---|---|---|---|---|---|
| Natural Gas at Forecourt | 75% | 45% | 20% | 6% | 2% |
| Biofuels at Forecourt | 20% | 25% | 15% | 10% | 6% |
| Biomass Gasification | 4% | 18% | 29% | 37% | 40% |
| Renewable & Nuclear Electrolysis | 1% | 8% | 20% | 22% | 22% |
| Coal Gasification with CCS | 0% | 5% | 16% | 25% | 29% |

Summary Greet 1.8a.XLS; Tab 'Fuel TS'; H 120 3/1 /2009

# Why Hydrogen from Ethanol?

| | | |
|---|---|---|
| ICV fuel economy | **25** | mpgge |
| HEV mpg/ ICV mpg | **1.45** | |
| FCEV mpg/ ICV mpg | **2.4** | |
| SMR HHV Efficiency | **76%** | |




Why hydrogen from ethanol.XLS; Tab 'Chart'; Q 31 2/24 /2009

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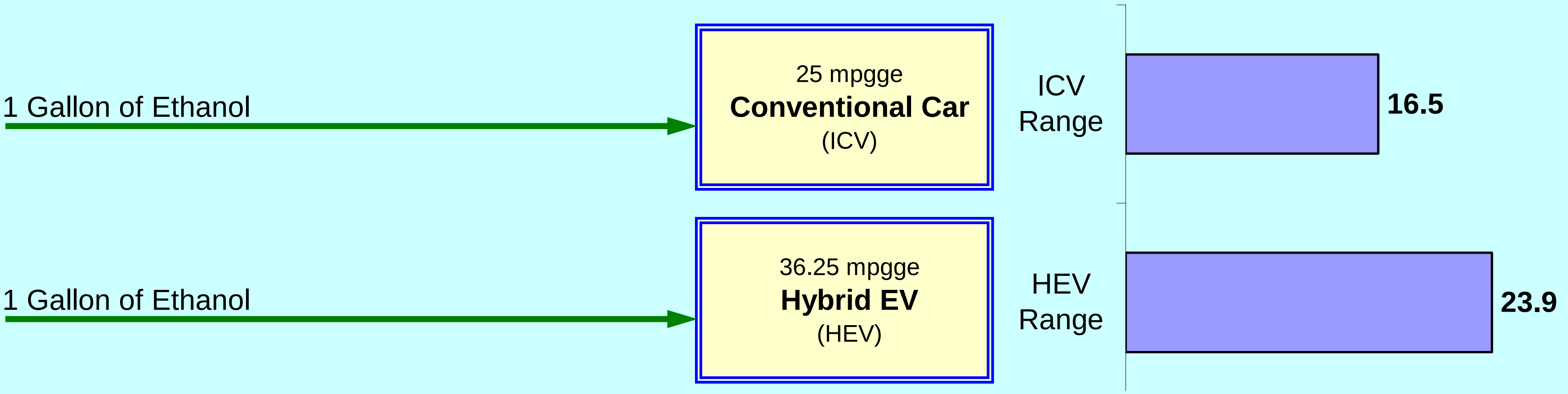


Why hydrogen from ethanol.XLS; Tab 'Chart'; Q 31 2/24 /2009

# Why Hydrogen from Ethanol?

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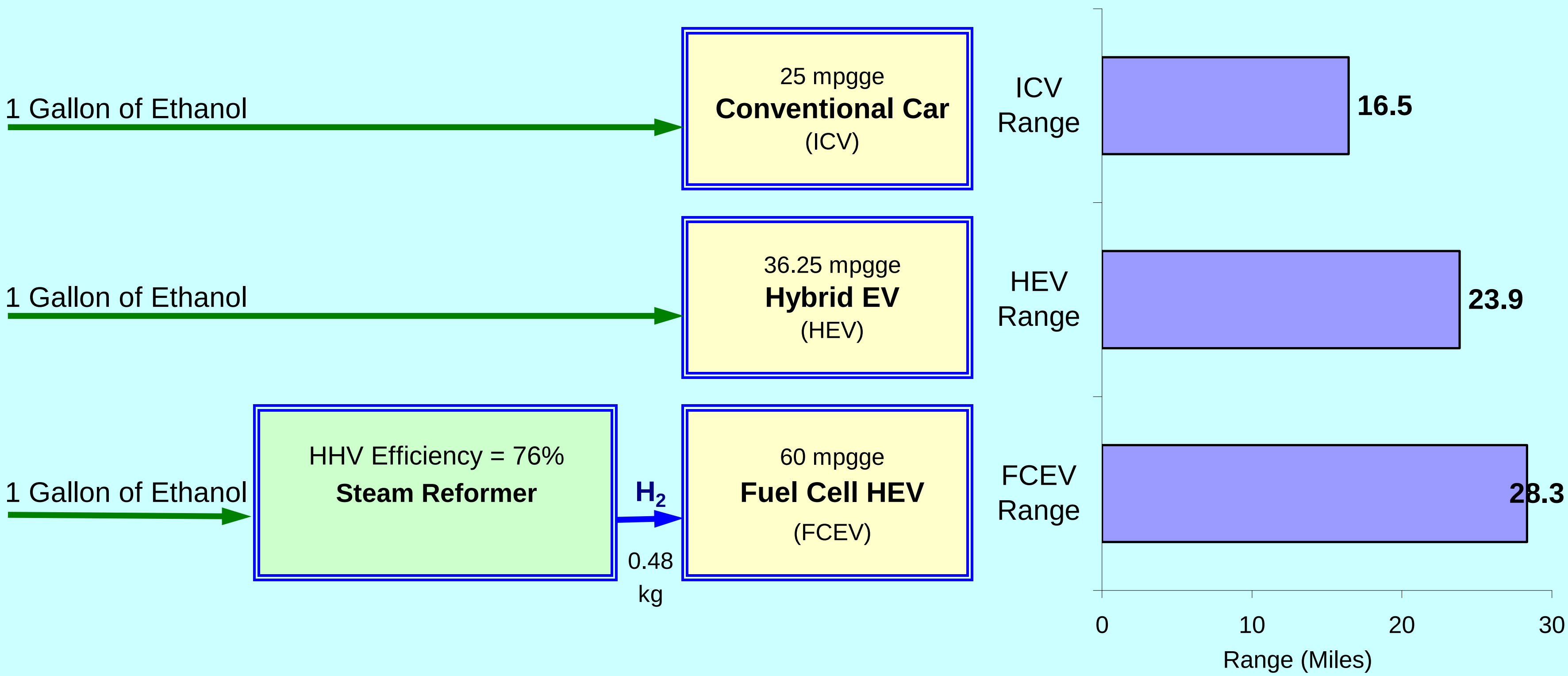


Why hydrogen from ethanol.XLS; Tab 'Chart'; Q 31 2/24 /2009

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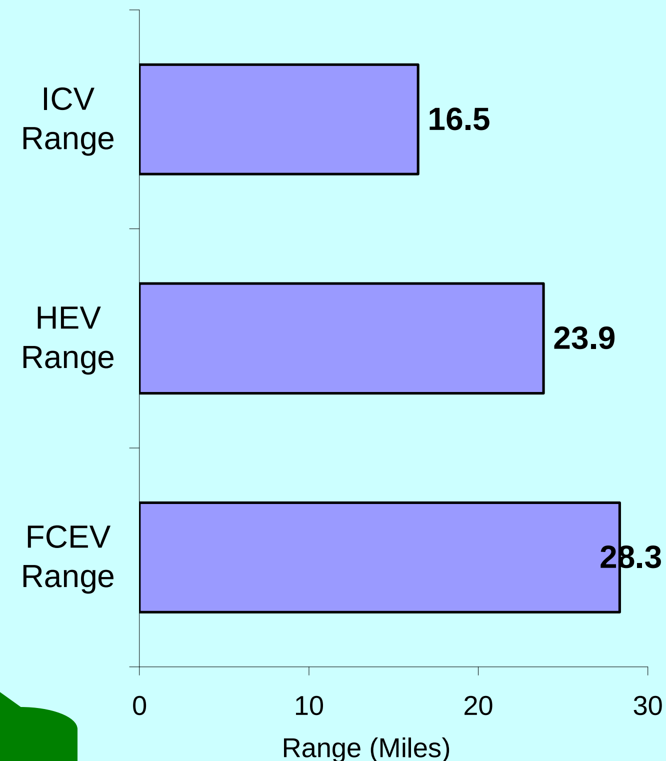
| FCEV Range Increase Factors | |
|---|---|
| w/r to ICV: | **1.72** |
| w/r to HEV | **1.19** |

1 Gallon of Ethanol → 25 mpgge **Conventional Car** (ICV)

1 Gallon of Ethanol → 36.25 mpgge **Hybrid EV** (HEV)

1 Gallon of Ethanol → HHV Efficiency = 76% **Steam Reformer** → $H_2$ 0.48 kg → 60 mpgge **Fuel Cell HEV** (FCEV)

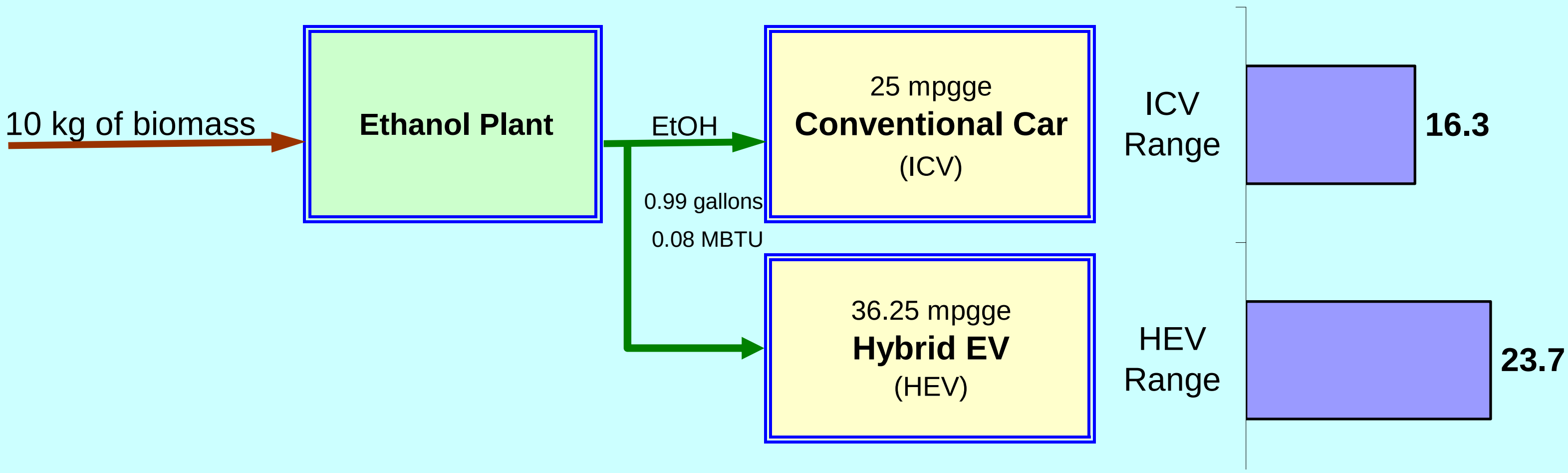
+ Zero Emissions




Hydrogen Production Efficiency.XLS; Tab 'Chart'; Q 31 3/6 /2009

# Consider Biomass Feedstock

| | | |
|---|---|---|
| ICV fuel economy | **25** | mpgge |
| HEV mpg/ ICV mpg | **1.45** | |
| FCEV mpg/ ICV mpg | **2.4** | |
| Biomass Gasifier LHV Efficiency | **49%** | |
| Ethanol Plant Productivity | **90** | gal EtOH/ton biomass |



# Better yet: Biomass Gasification

| | | |
|---|---|---|
| ICV fuel economy | **25** | mpgge |
| HEV mpg/ ICV mpg | **1.45** | |
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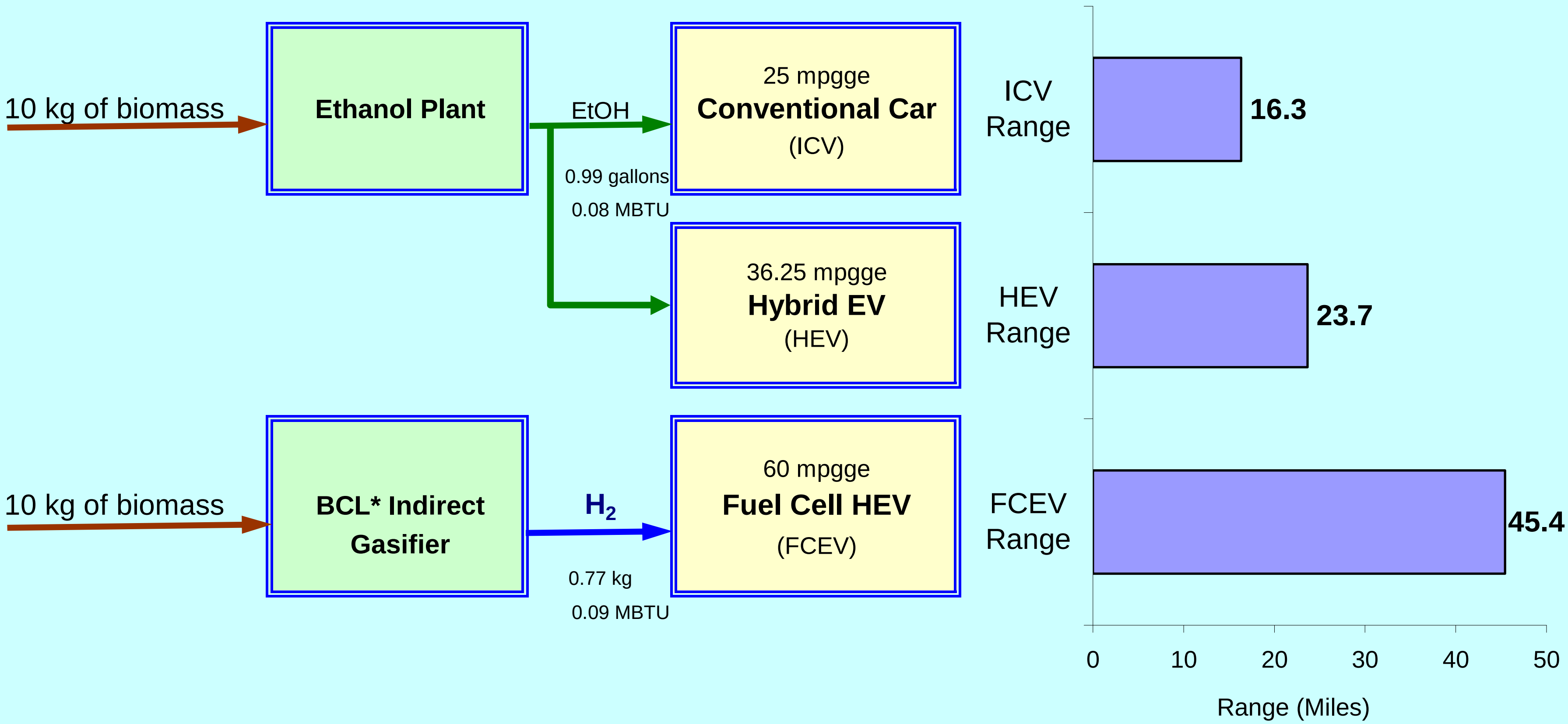


BCL* = Battelle Columbus Laboratory

Why hydrogen from ethanol.XLS; Tab 'Chart Biomass'; Q 32 2/24 /2009

# Biomass Gasification

| | | |
|---|---|---|
| ICV fuel economy | **25** | mpgge |
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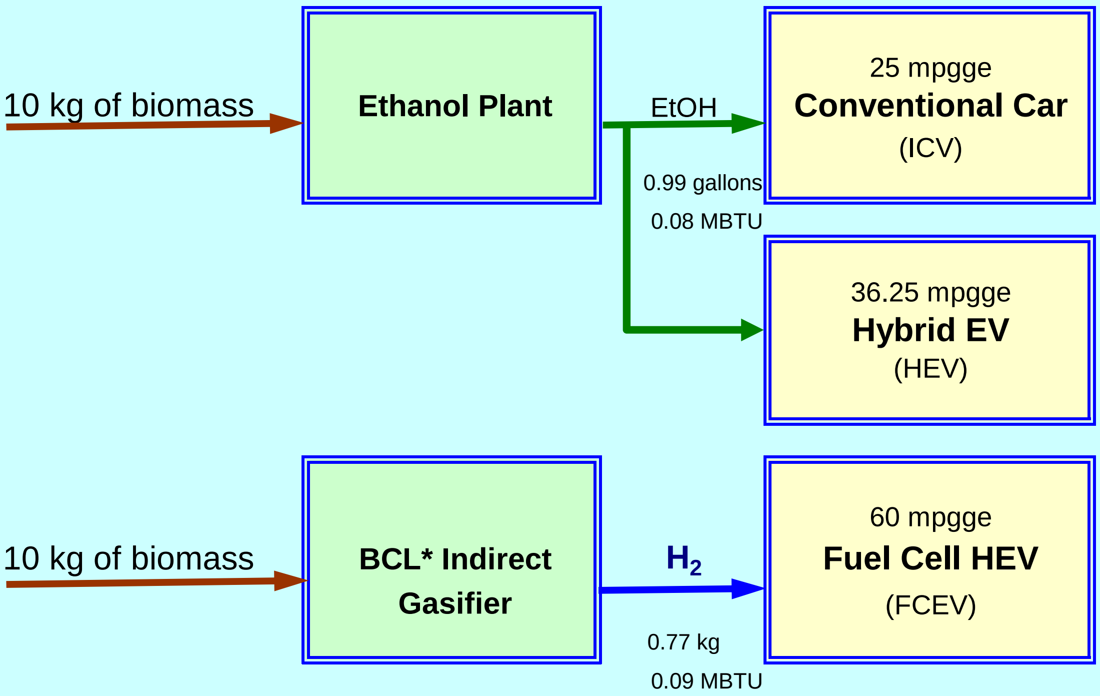
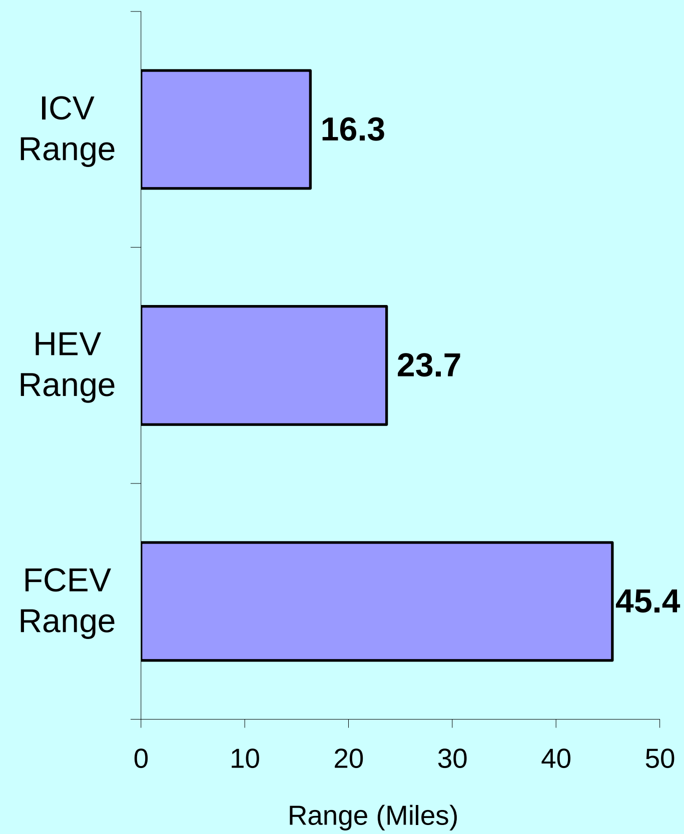
| FCEV Range Increase Factors | |
|---|---|
| w/r to ICV: | **2.8** |
| w/r to HEV | **1.9** |




BCL* = Battelle Columbus Laboratory

Why hydrogen from ethanol.XLS; Tab 'Chart Biomass'; Q 32 3/6 /2009

# What fuels?

- Gasoline?
- Biofuels*?
- Hydrogen?
- Diesel?
- Natural Gas?
- Electricity?

**Renewable Fuels**

*Butanol, cellulosic ethanol, etc.

# Four Major Scenarios

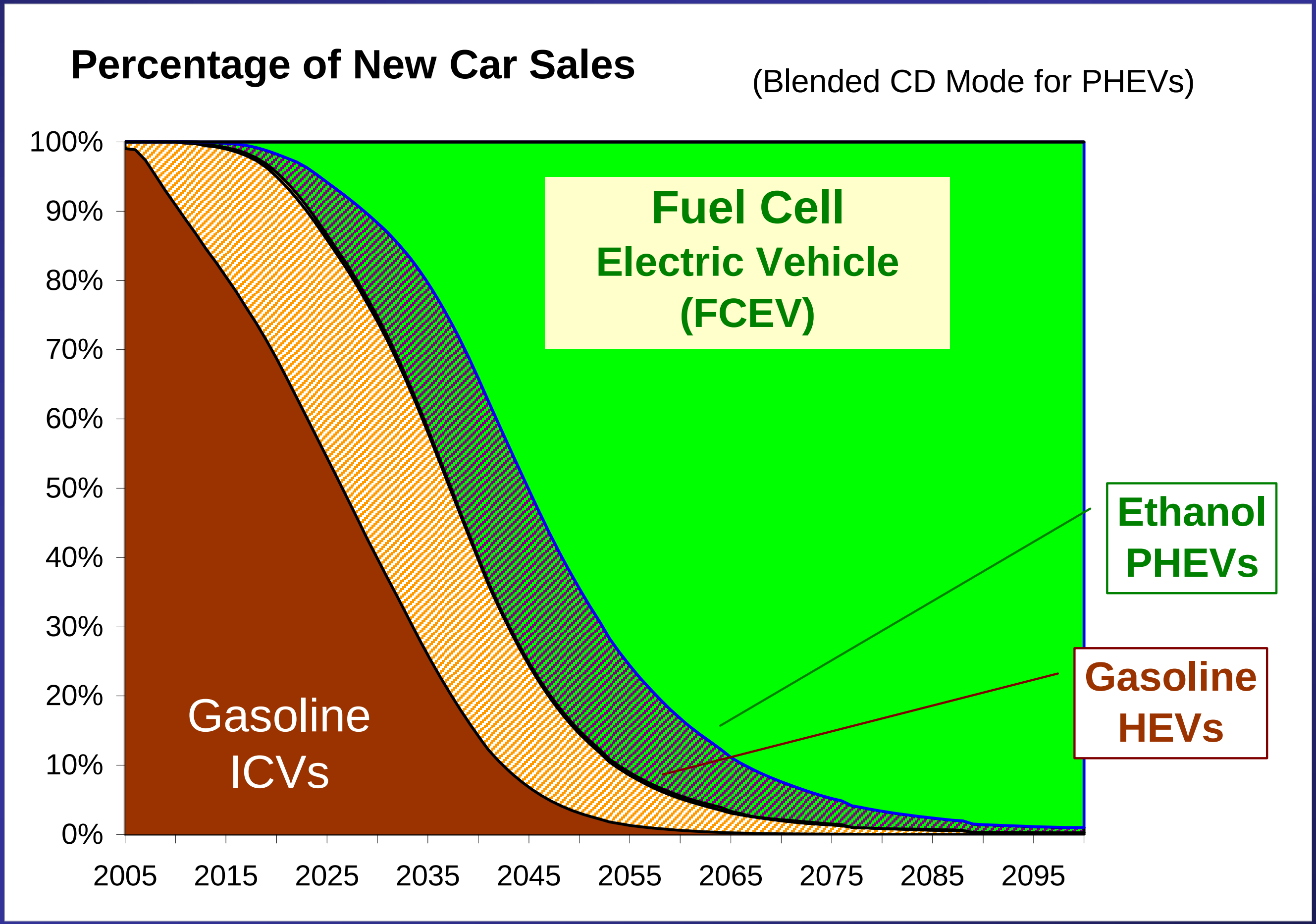
- Gasoline ICE Hybrid Electric Vehicle (HEV) Scenario
- Gasoline ICE Plug-In Hybrid Electric Vehicle (PHEV) Scenario
- (Cellulosic) Ethanol ICE PHEV Scenario
- Hydrogen Fuel Cell Electric Vehicle (FCEV)* Scenario

*& Two Secondary Scenarios:*

- *Battery Electric Vehicles (BEV)*
- *Hydrogen ICE Hybrid Electric Vehicles (H2 ICE HEV)*

** FCEV includes peak power augmentation with batteries or ultracapacitors*

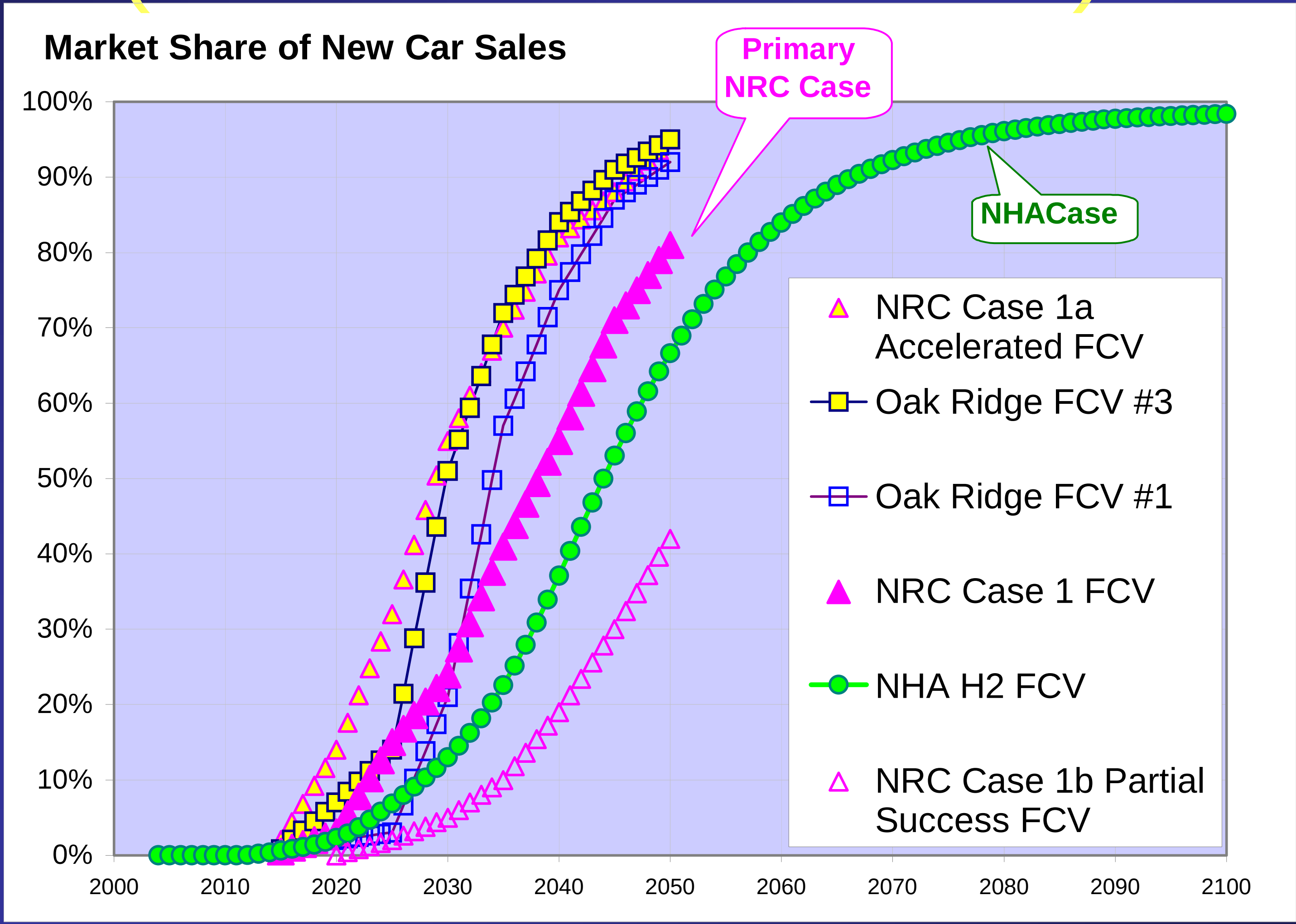
# Fuel Cell Electric Vehicle
## (& BEV, H2 ICE HEV)
# Scenario Market Shares




Story Simultaneous.XLS; Tab 'Graphs'; ED 30 7/2 /2009

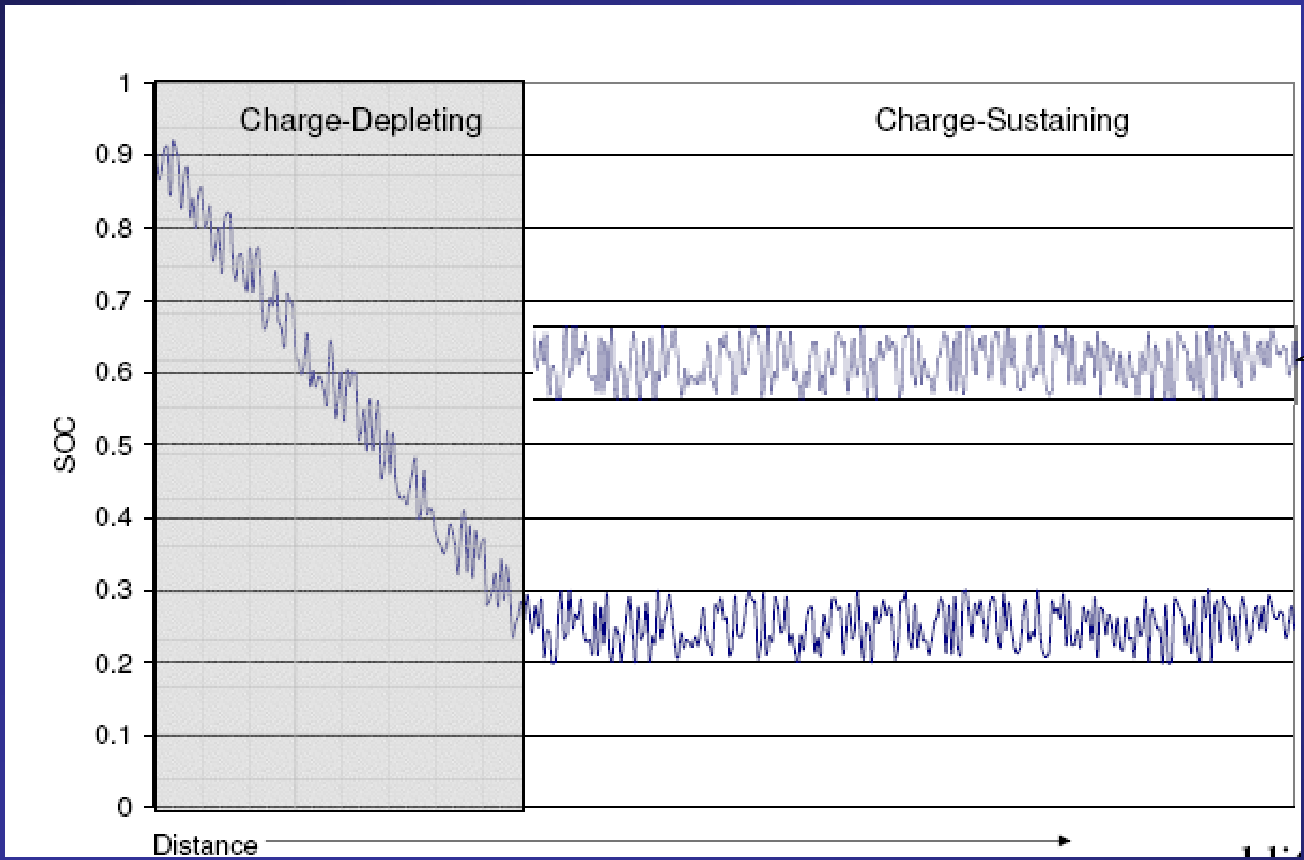
(50% Market Share Potential by 2035)

# FCV Market Penetration Rates: (NRC & ORNL vs. NHA)




H2 Energy Story.XLS; Tab 'Annual Sales';IK 211 7/19 /2008

# PHEV Charging Modes



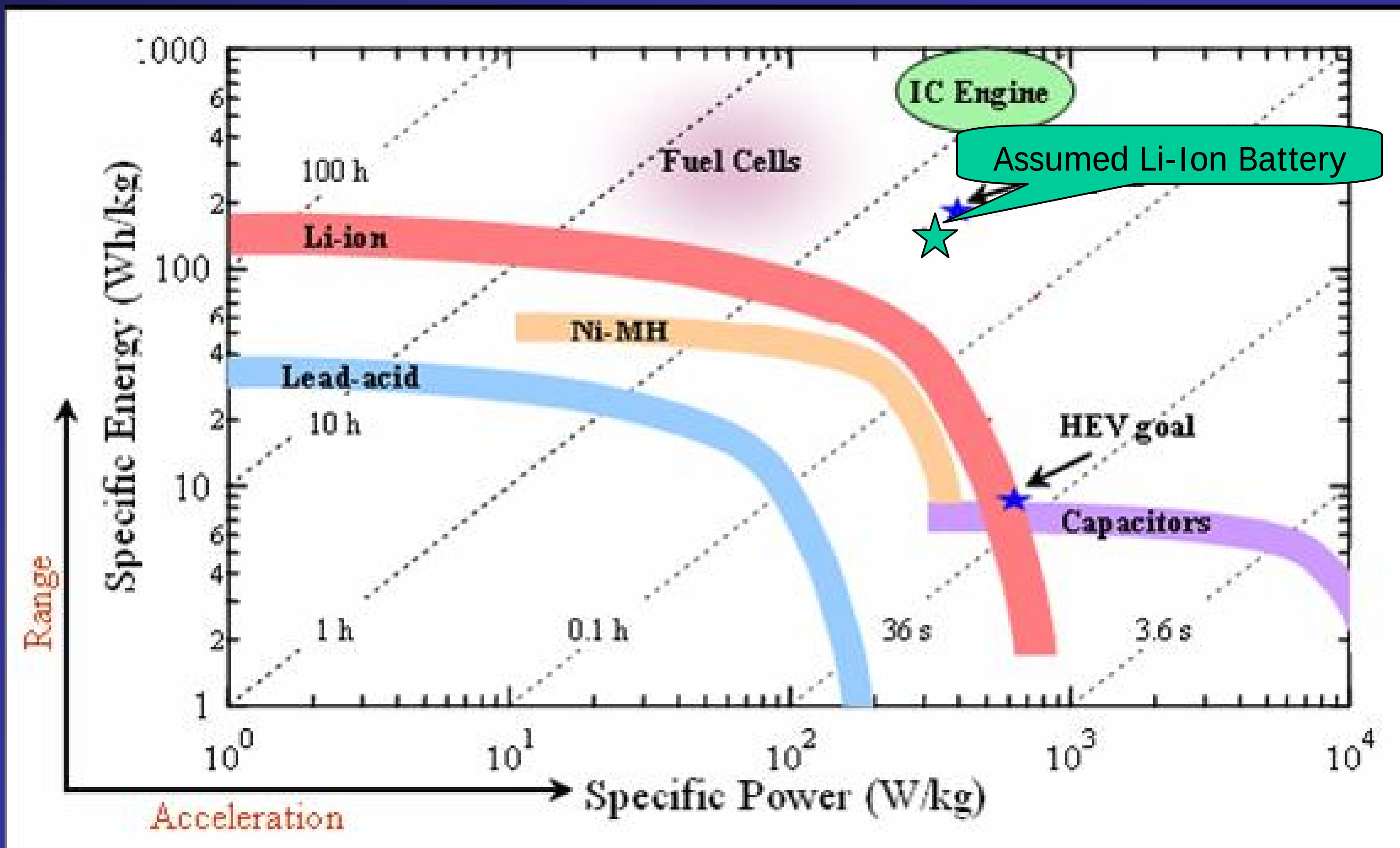

HEV Operation

[Ref: Kromer & Heywood, MIT]

**Blended** Charge-Depleting Mode:

On-board power source (ICE or FC) used for peak power boost during CD mode.

# Battery Power vs. Energy Trade-off




Ref: Kromer, Matthew & J.B. Heywood, "Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet," Sloan Automotive Laboratory, Massachusetts Institute of Technology, Publication Number LFEE 2007-03 RP, May 2007

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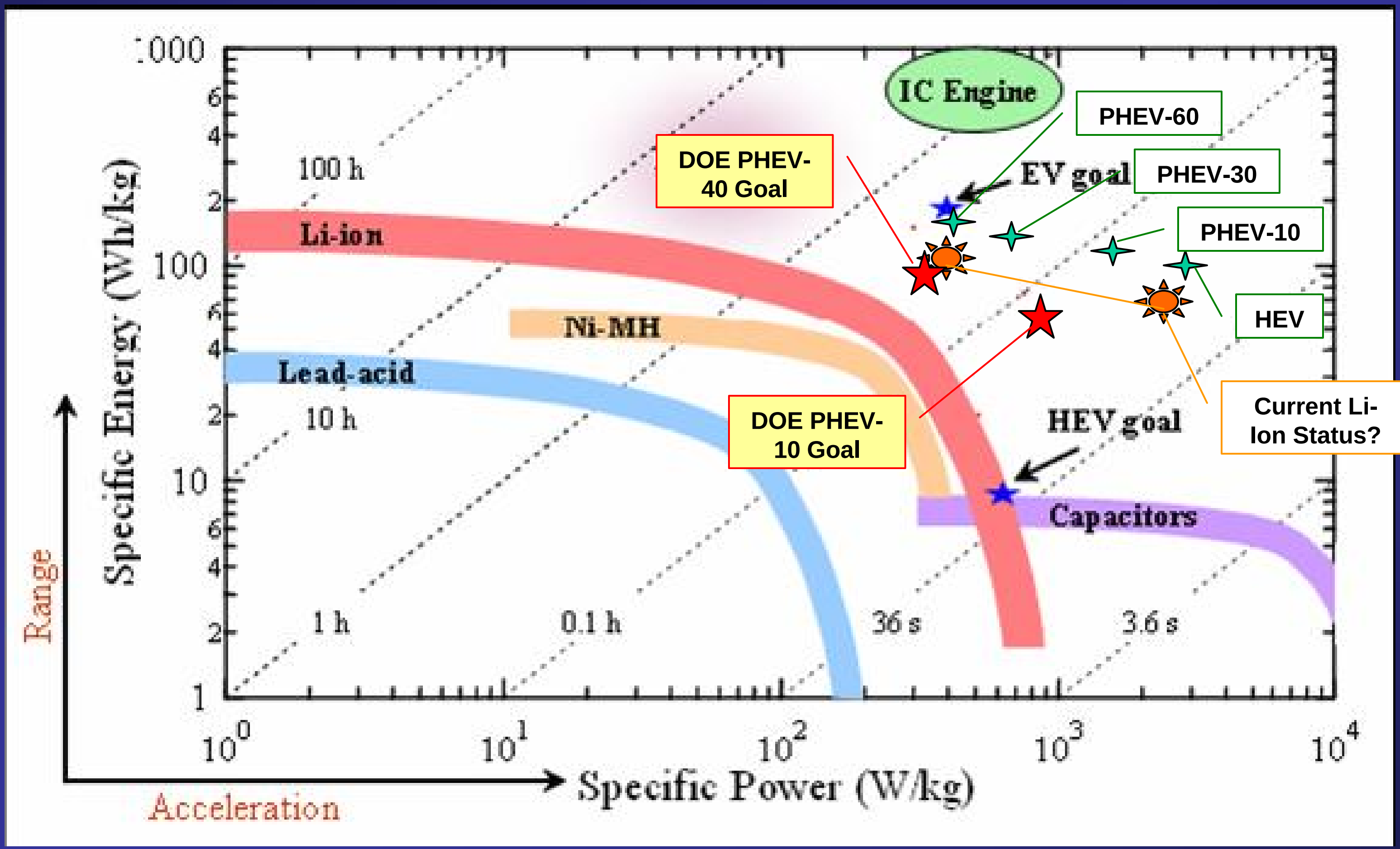


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# Utility Factor*

[Charge depleting (CD) mode distance/ Total distance]

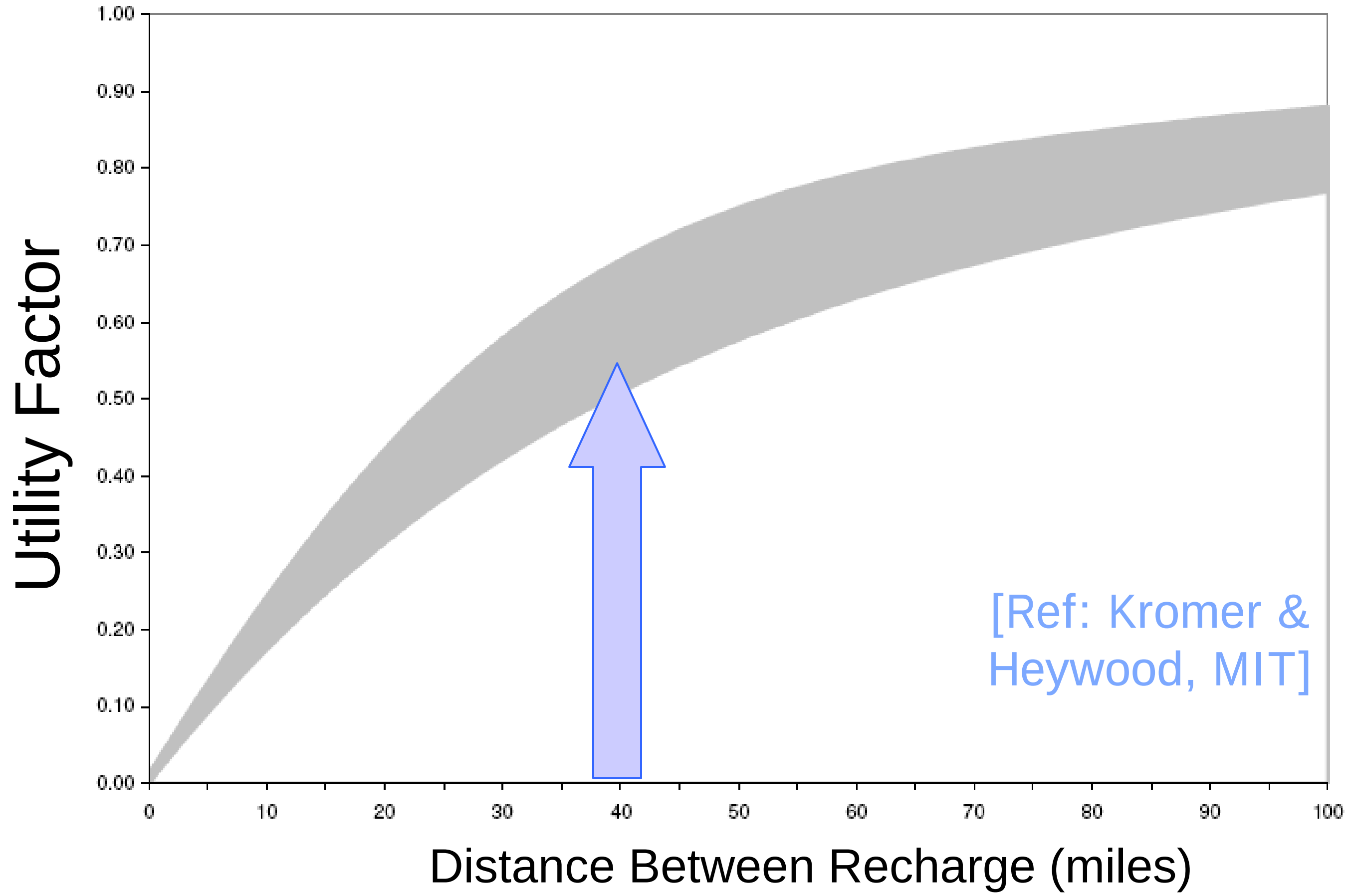
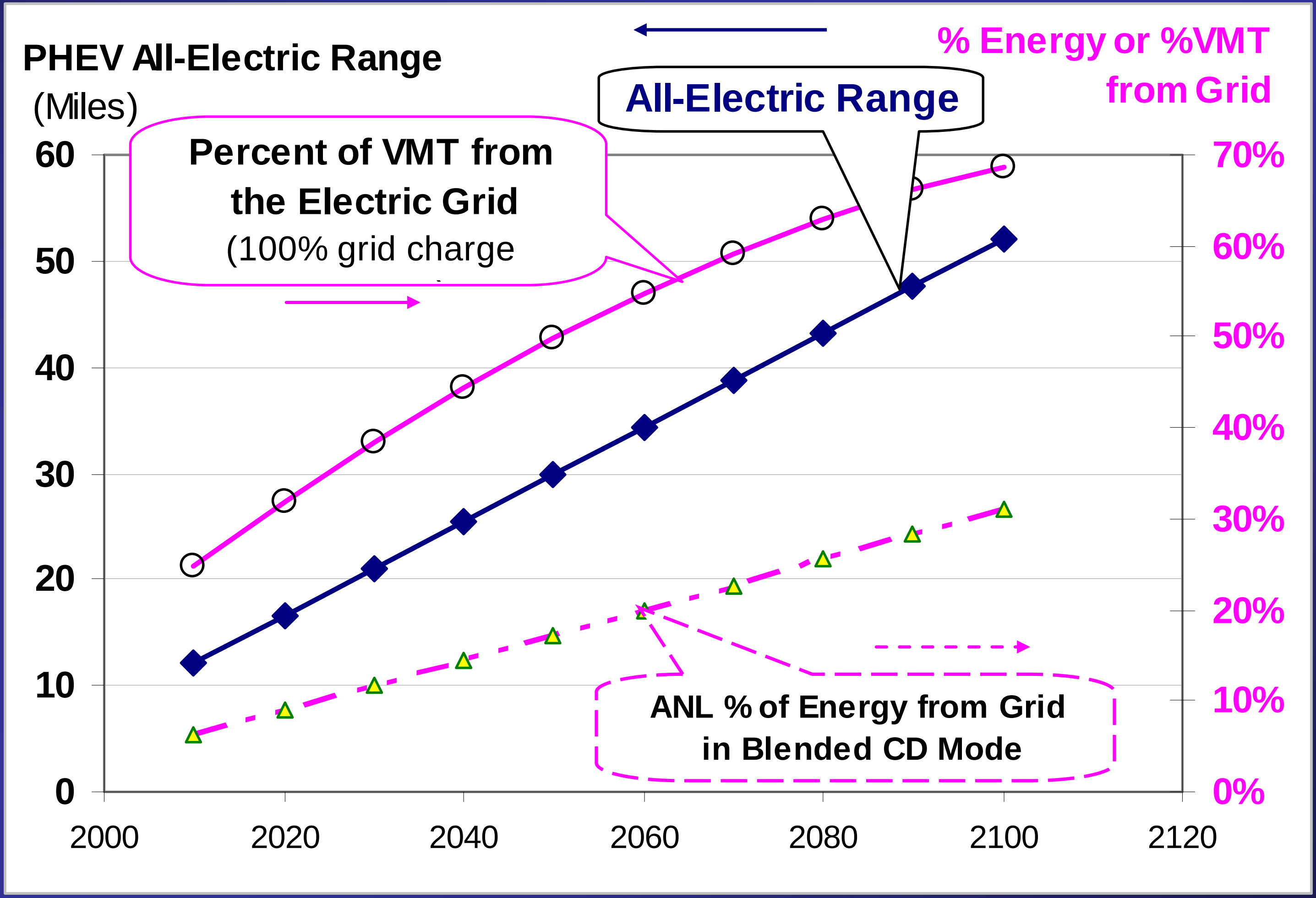



**Figure 23: Estimated utility curves as a function of vehicle range: estimates from a number of different sources. Data derived from SAE J1711, EPRI 2001, Markel 2006, and ORNL 2004.**

*Utility Factor = fraction of miles traveled in charge depleting (CD) mode

# Plug-in Hybrid Assumptions




Source: EPRI /NRDC report on PHEVs & ANL SAE Paper

# Google Real-World Measurement of PHEV Fuel Economy*

H2Gen

| |  |  |  |
|---|---|---|---|
| **Model** | Toyota Prius Plugin | Toyota Prius | US fleet average |
| **MPG** | 57.6 | 42.1 | 19.8[1] |
| **Wh/mile** | 131.5 | — | — |
| **$CO_2$e lbs/mile[2]** | 0.474 | 0.560[4] | 1.192[3] |
| **$CO_2$e emissions saved** | 60% | 53%[4] | |
| **Gallons of gasoline saved per year[6]** | 398 | 321 | |
| **Barrels of oil saved[7]** | 66% | 53% | |
| **Percent of US fleet to halve $CO_2$e emissions[8]** | 83% | 94% | |
| **Cost savings in dollars per year[9]** | $1493 | $1333 | |

Current Payback Period: 60 years

($10,000 Li-Ion Battery Pack)

*Based on Google fleet of 8 retrofitted Prius PHEVs; est. AER = 25 miles with 4.7 kWh battery & 70% SOC; http://www.google.org/recharge/dashboard/calculator#notes

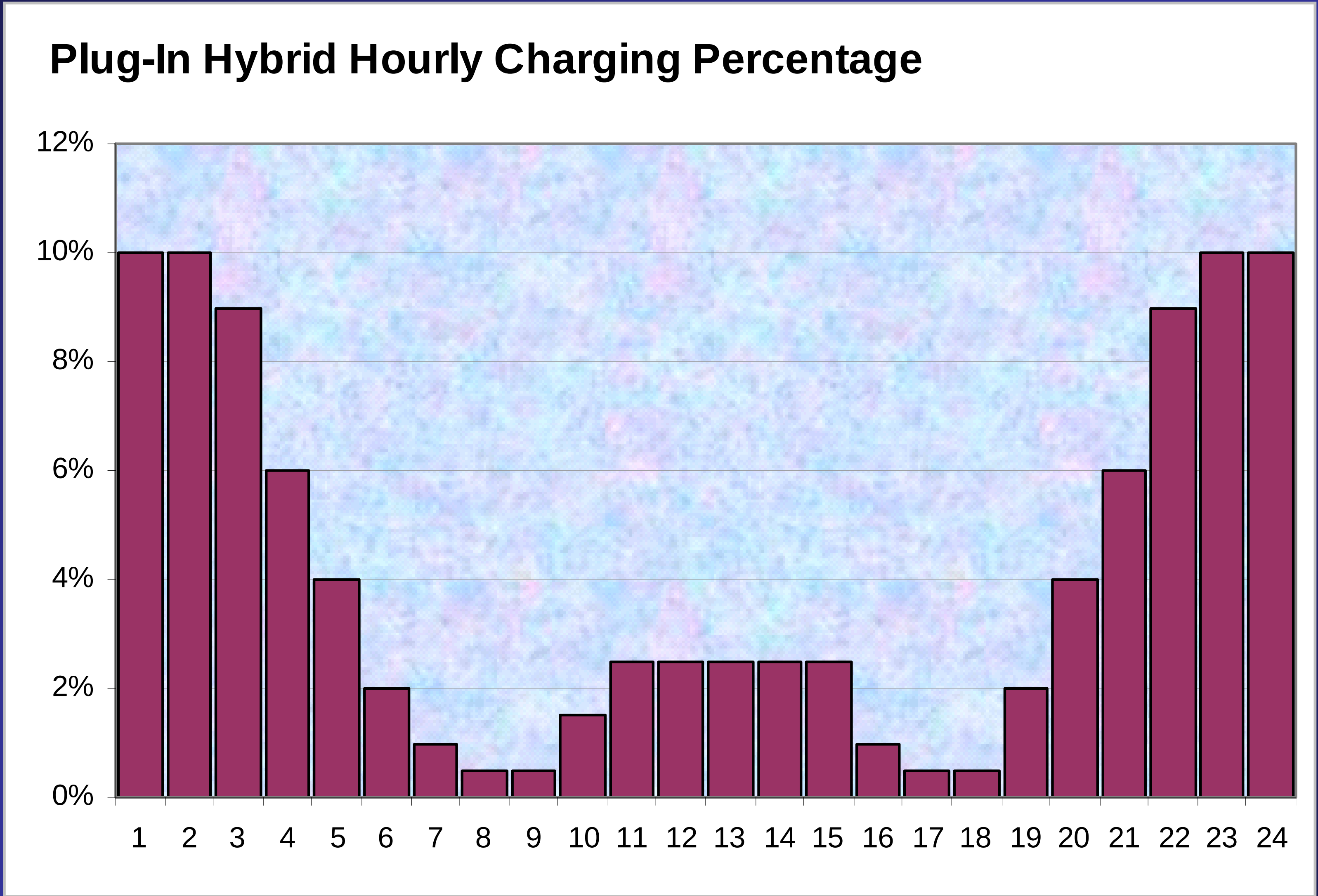
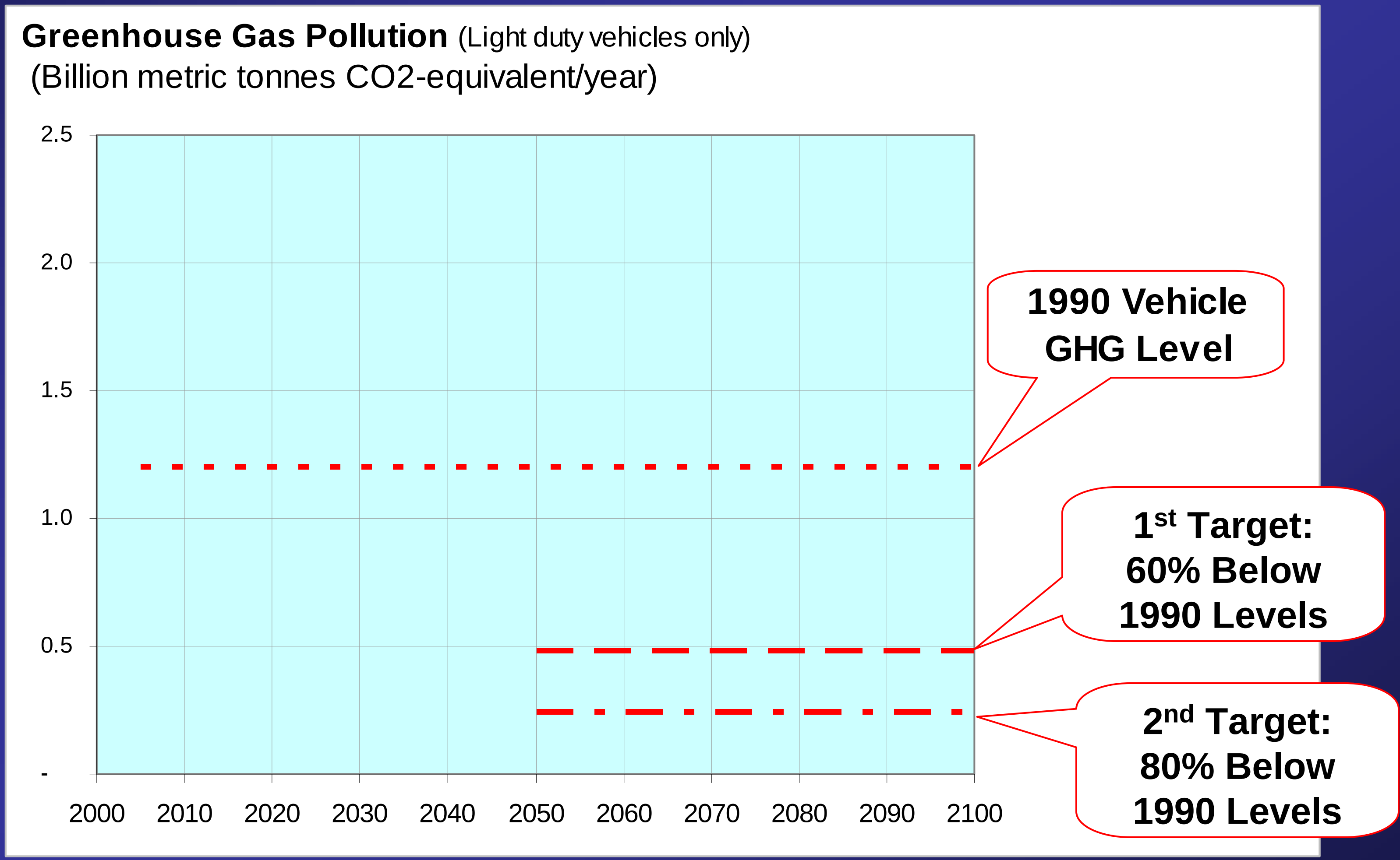
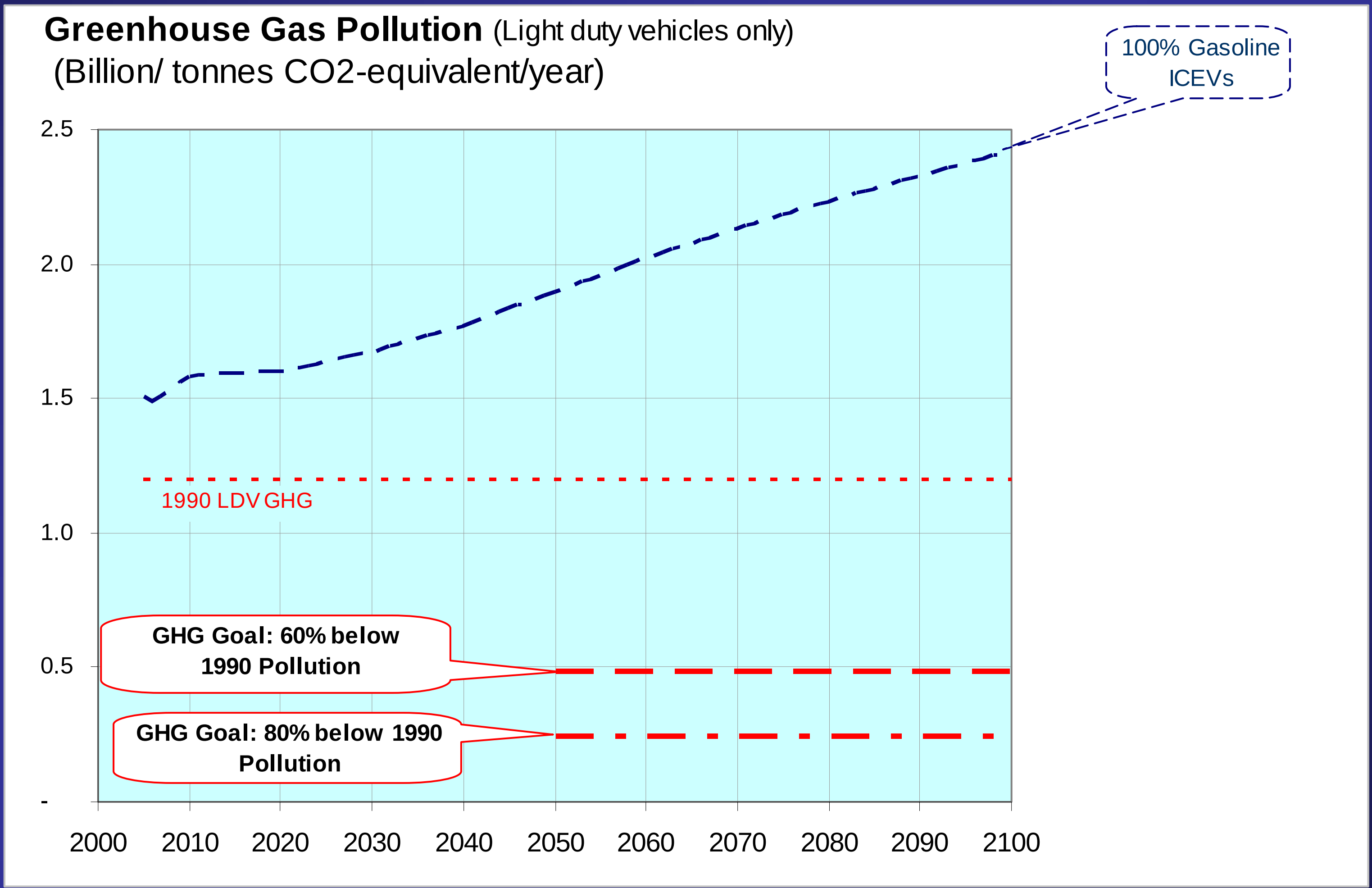



**Figure 1. PHEV charging profile suggested by EPRI**

# 1990 Baseline Transportation Greenhouse Gas (GHG) Emissions



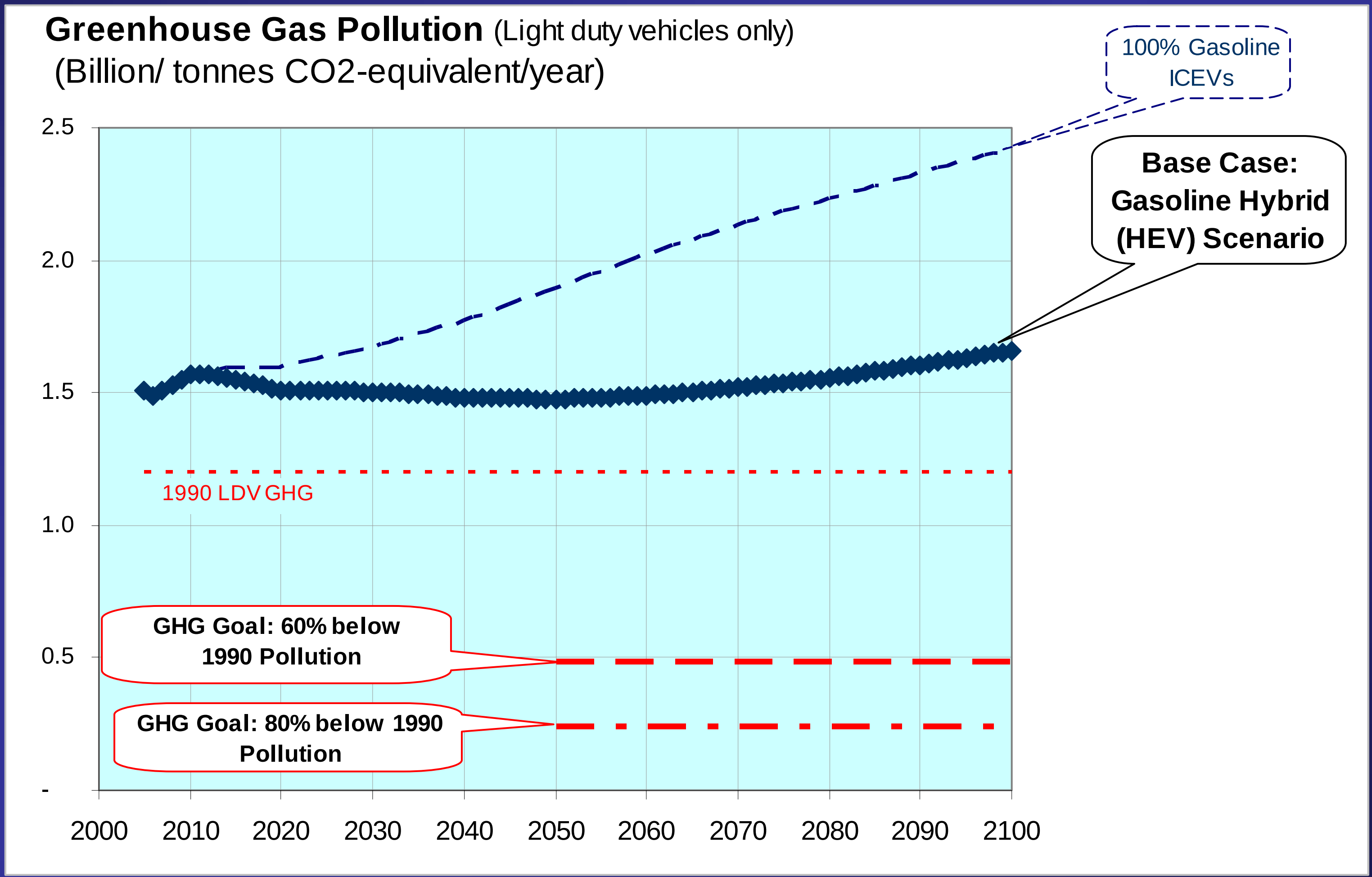
# GHG Reference Case: 100% Gasoline Cars






Sources: Argonne National Laboratory GREET 1.8a & AEO 2009 Projections for VMT thru 2030

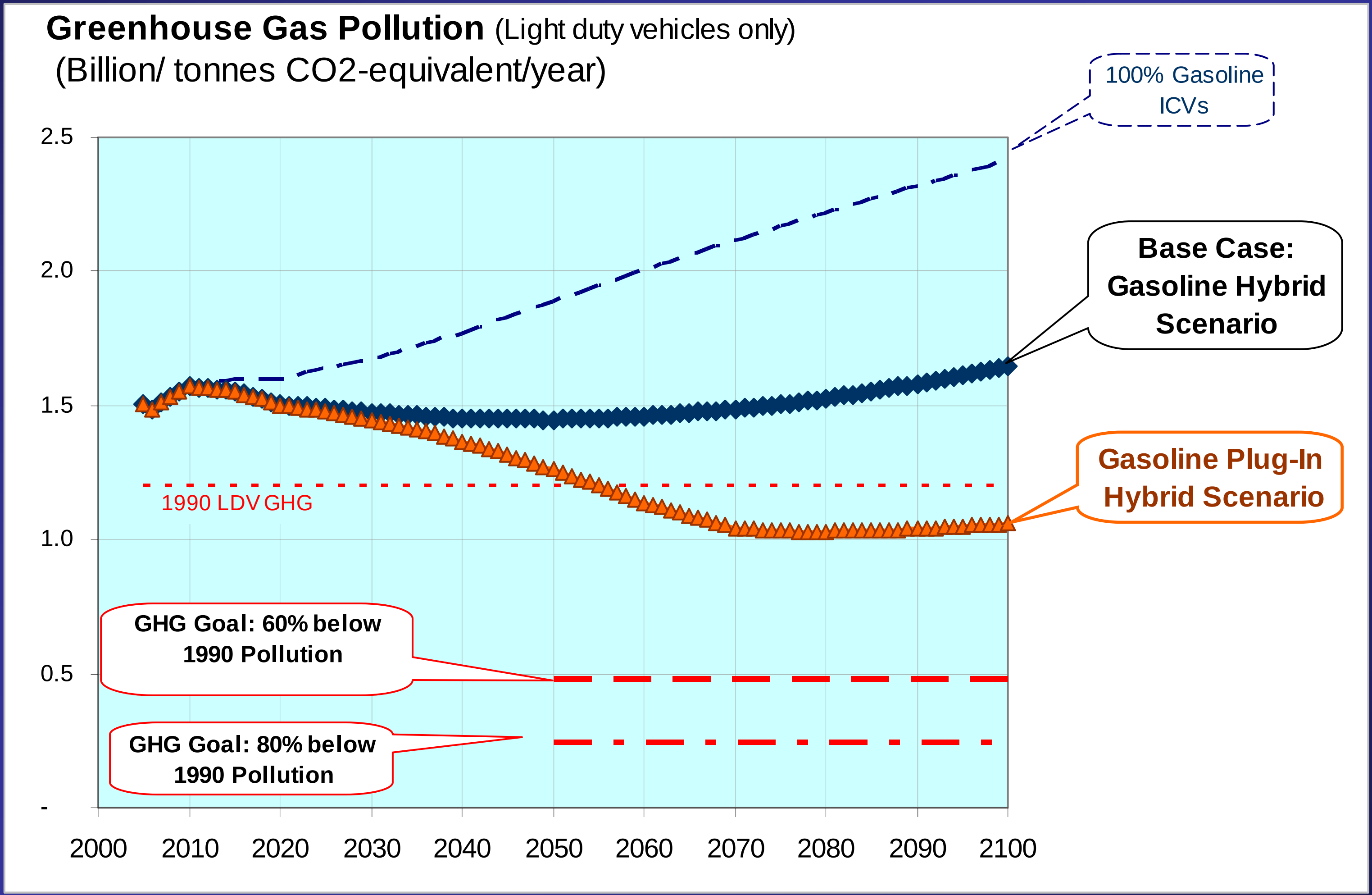
# GHG Base Case: Gasoline Hybrid Electric Vehicles (HEVs)




Sources: Argonne National Laboratory GREET 1.8a, AEO 2009 & NHA models

# GHG: Gasoline Plug-in Hybrid Electric Vehicles (PHEVs)

(75% night-time charging access)

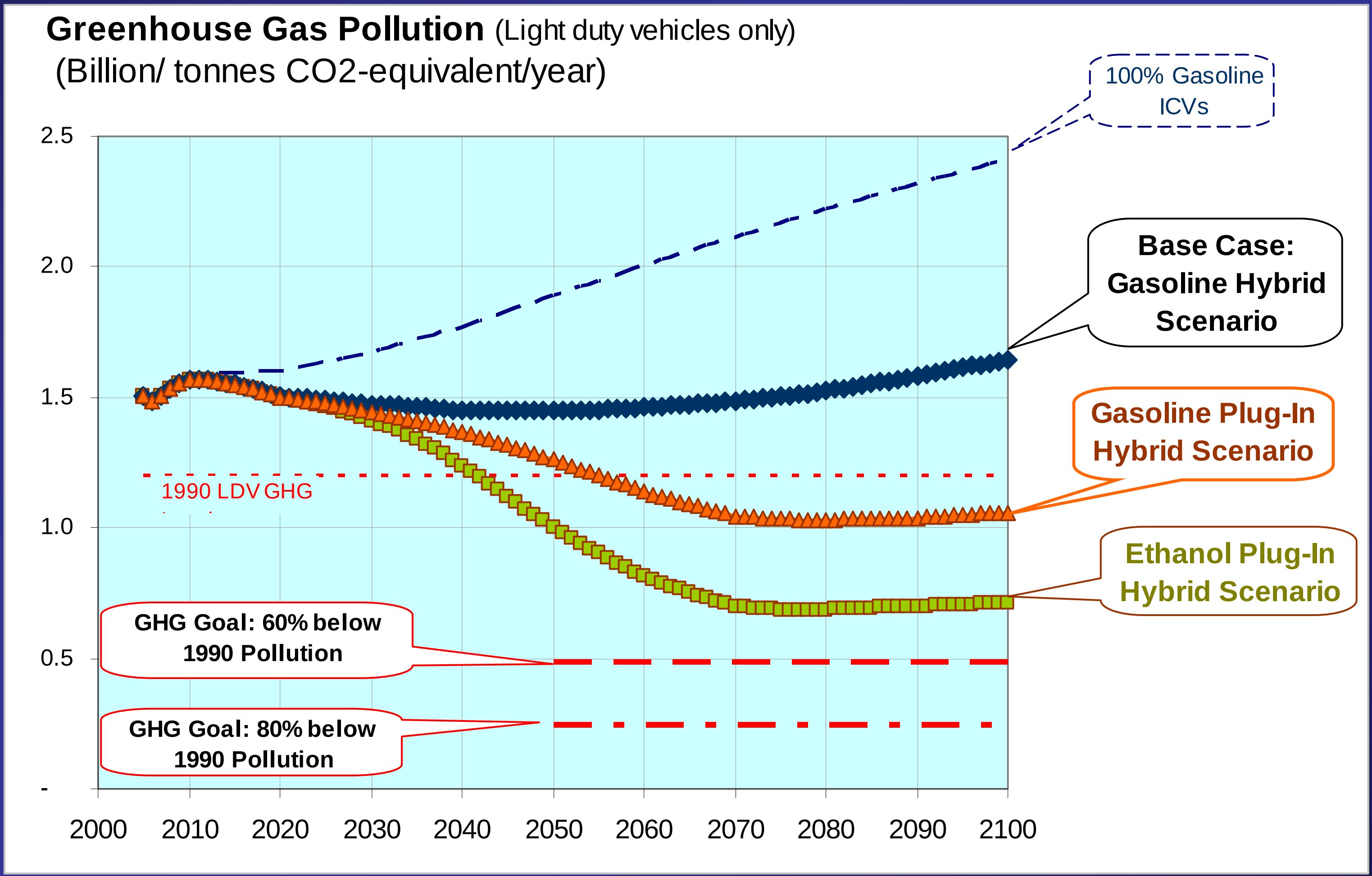





Sources: Argonne National Laboratory GREET 1.8a, AEO 2009 & NHA models

# GHG: Biofuel Plug-In Hybrids

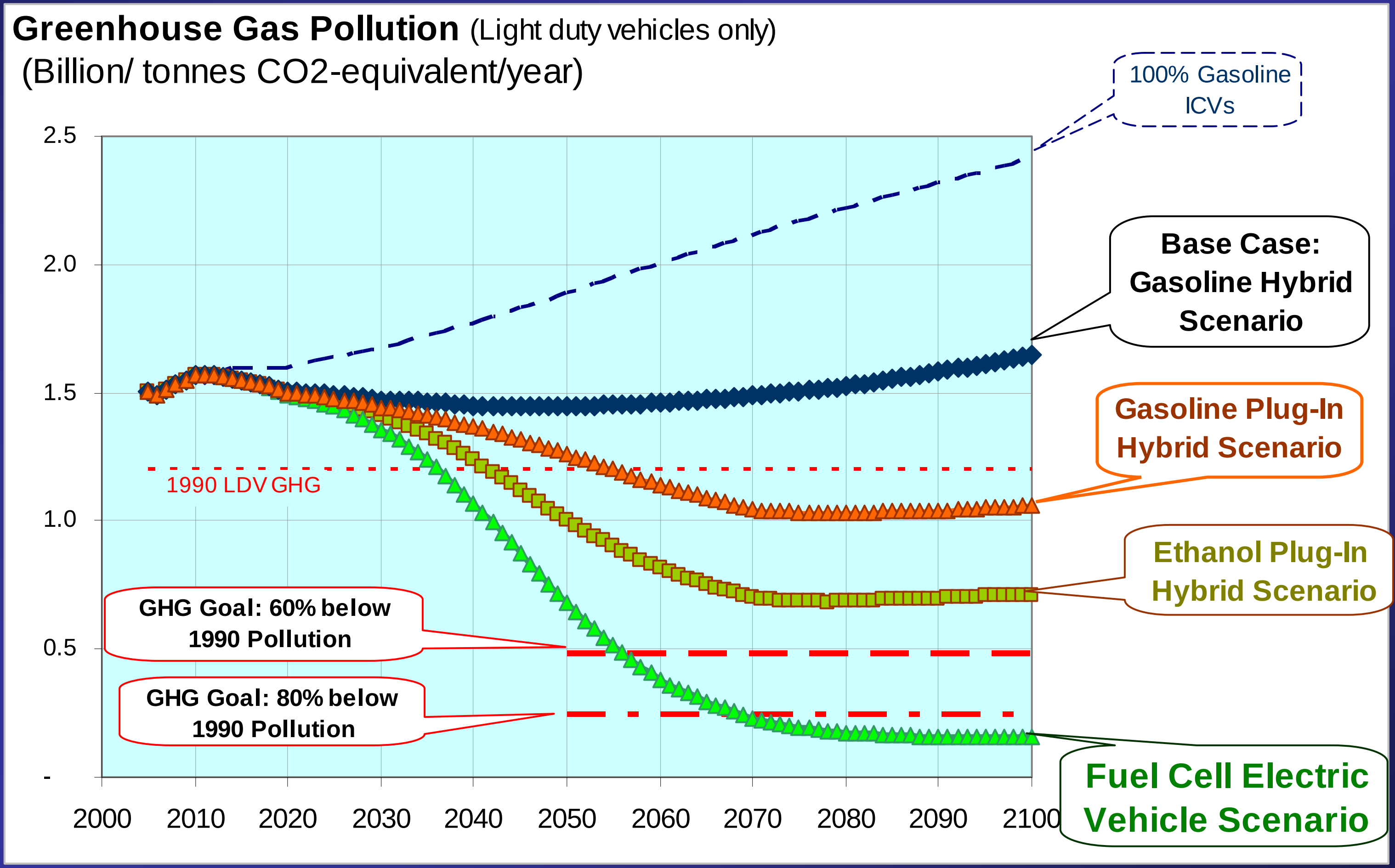
(90 Billion gallons/year* Cellulosic Ethanol)





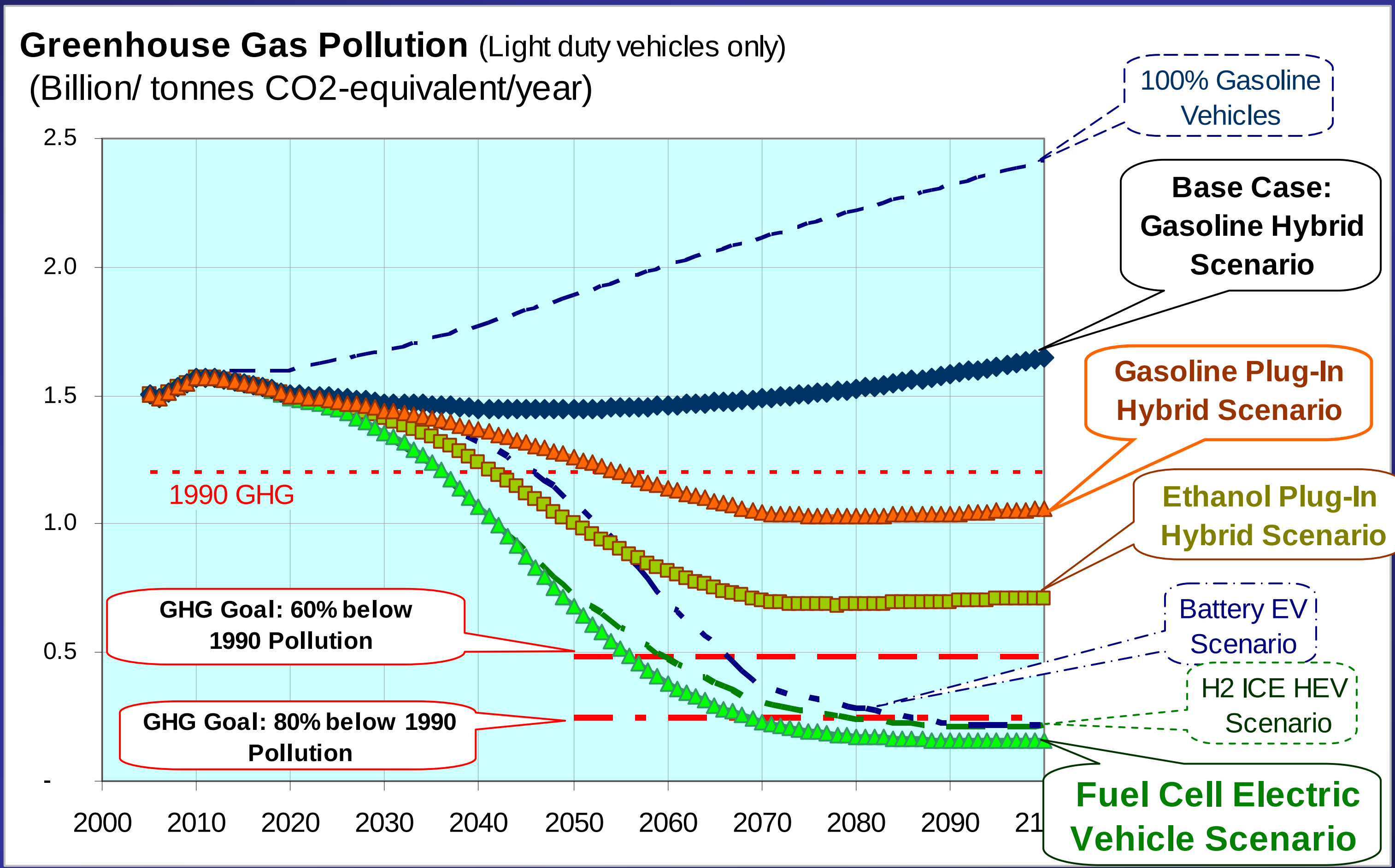

*Sandia-Livermore estimates 90 B gallons/yr potential; NRC uses 60 B gallons/yr maximum; current production of ethanol: 8 billion gallons/year; no limit on availability of night-time charging outlets

# GHG: Fuel Cell Vehicles




Sources: Argonne National Laboratory GREET 1.8a, AEO 2009 & NHA models

# GHG: $H_2$ ICE HEV & Battery EV




Sources: Argonne National Laboratory GREET 1.8a, AEO 2009 & NHA models

# PHEV GHGs (Kromer & Heywood, MIT, May 2007)

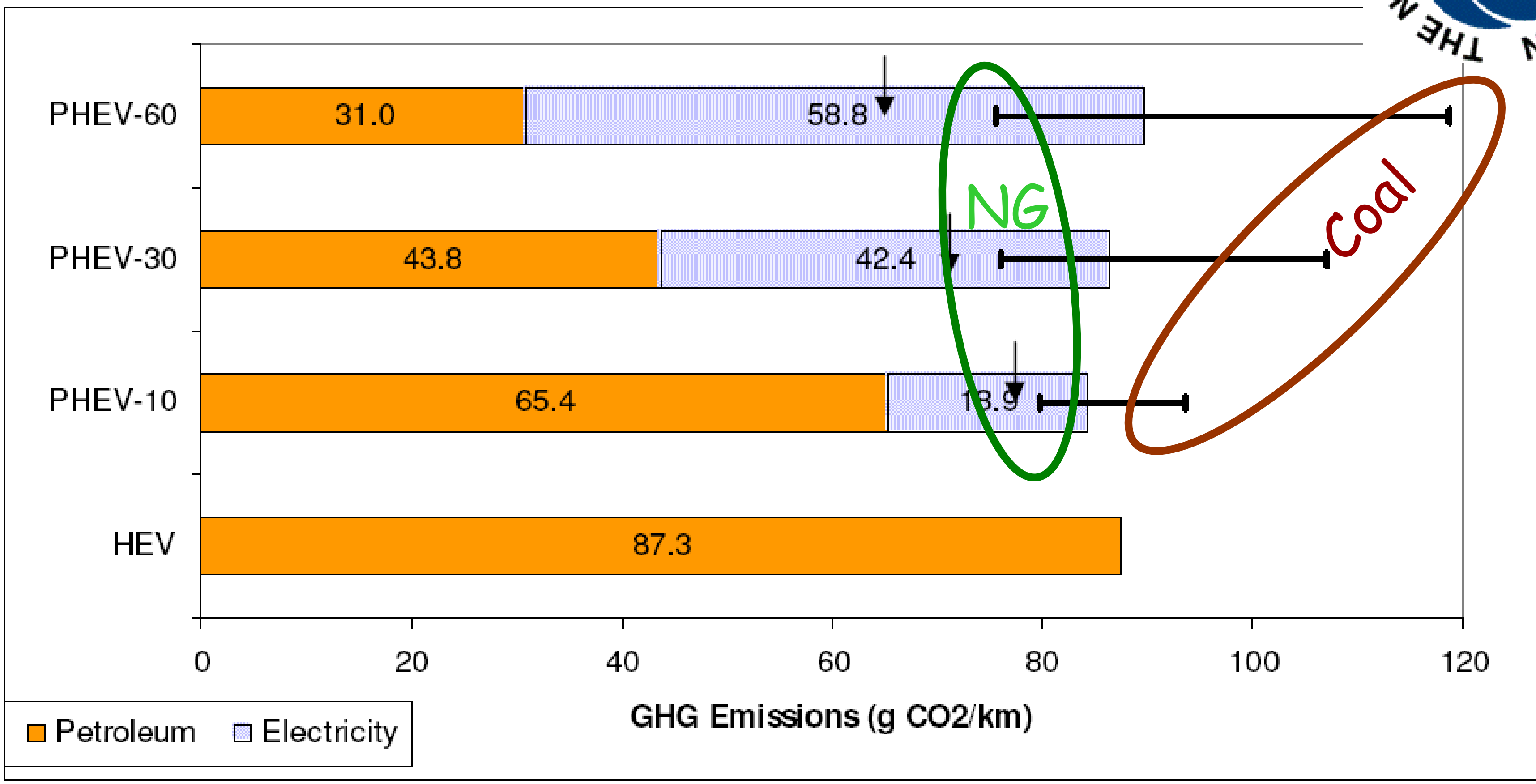
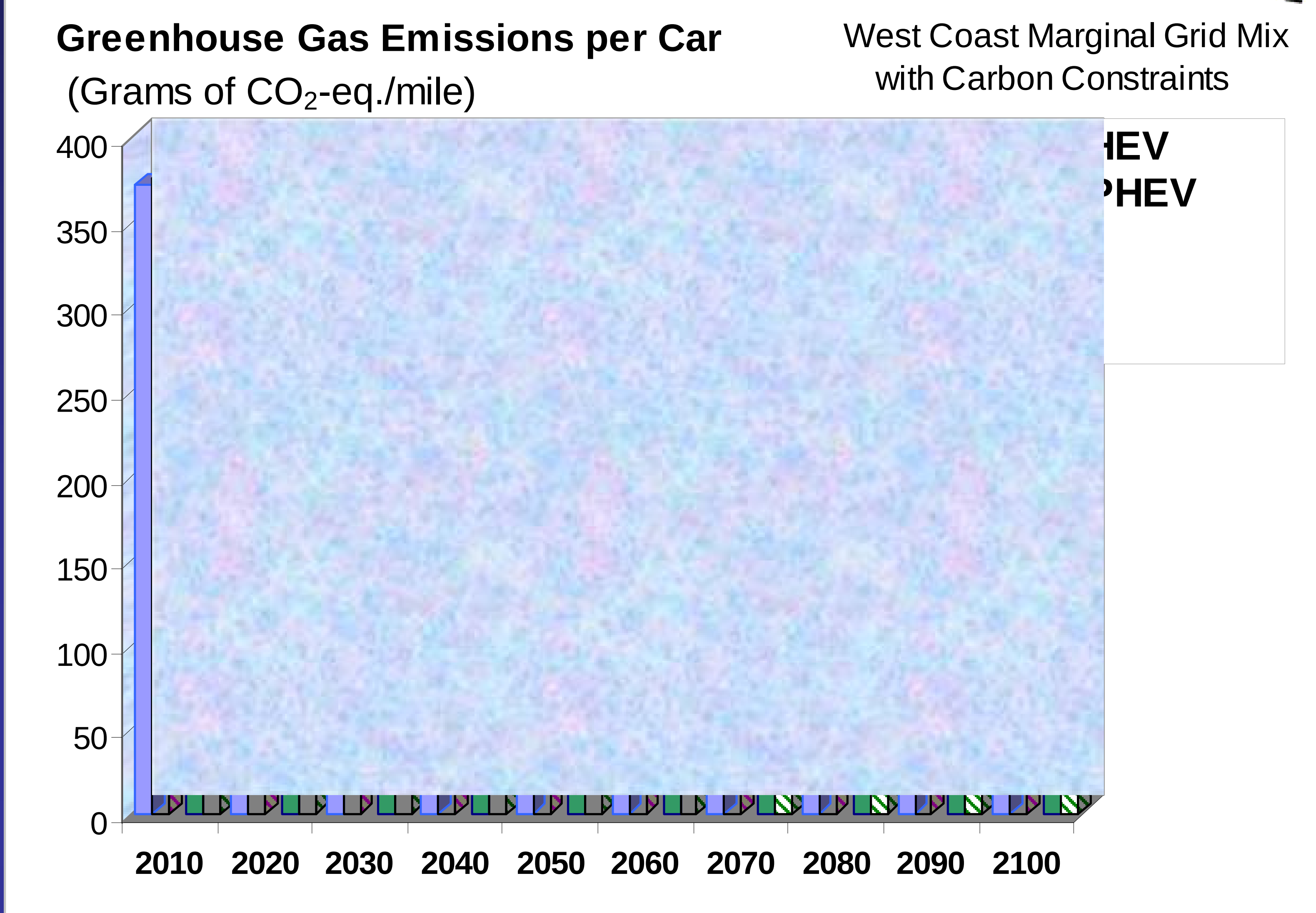



Figure 38: Breakdown of GHG emissions for the hybrid vehicle and plug-in hybrids with varying range. The low-end of the uncertainty bar corresponds to natural gas generation; the high-end corresponds to coal; and the base case corresponds to the average grid. The arrows indicate the emissions rate of the clean grid mix identified in section 5.7.4.



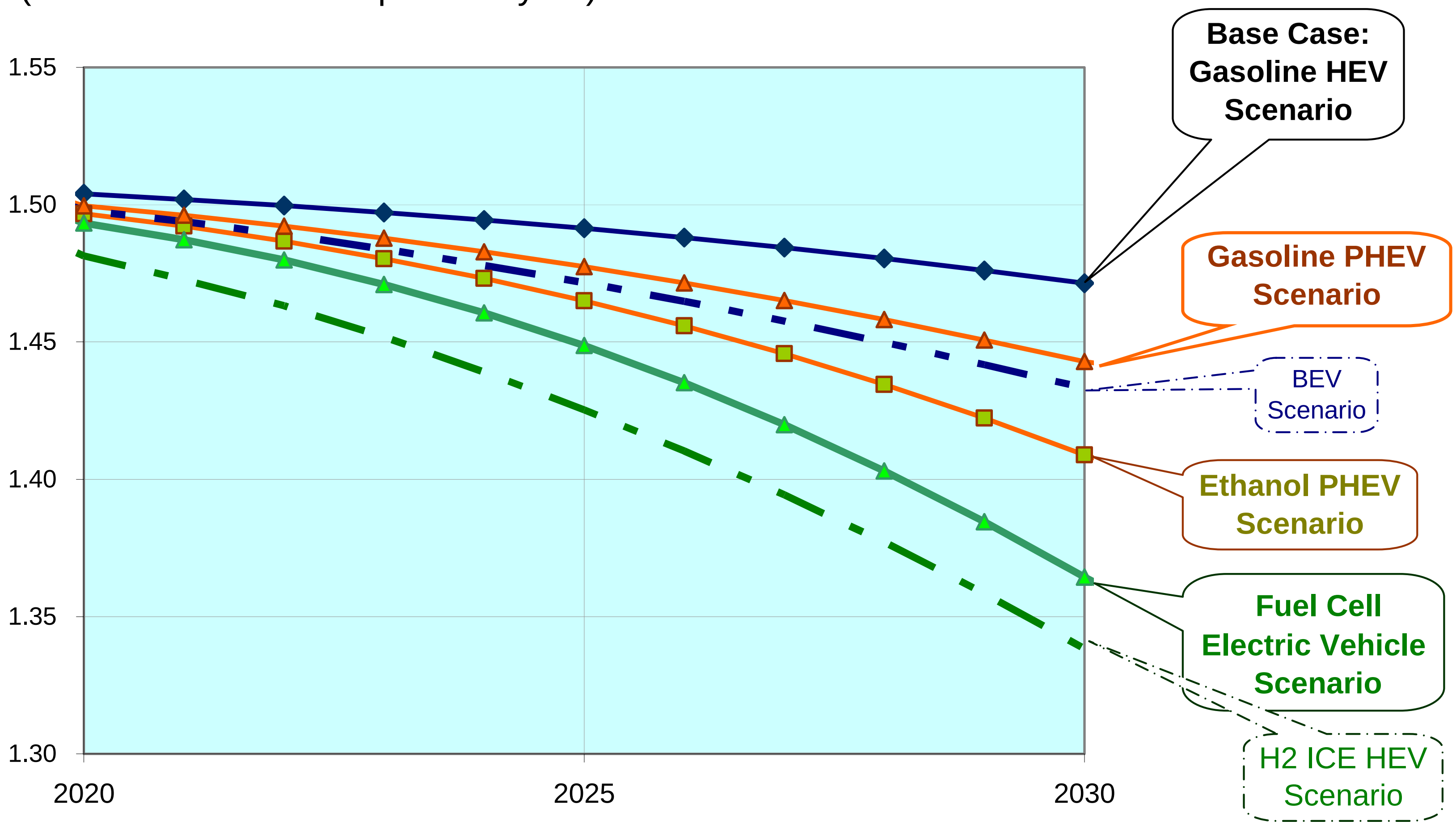
"Clean Grid" = 50% nuclear + renewables; 15% advanced NG CC & 35% advanced coal

# To Plug or Not to Plug?



# Early (2020 to 2030) GHGs

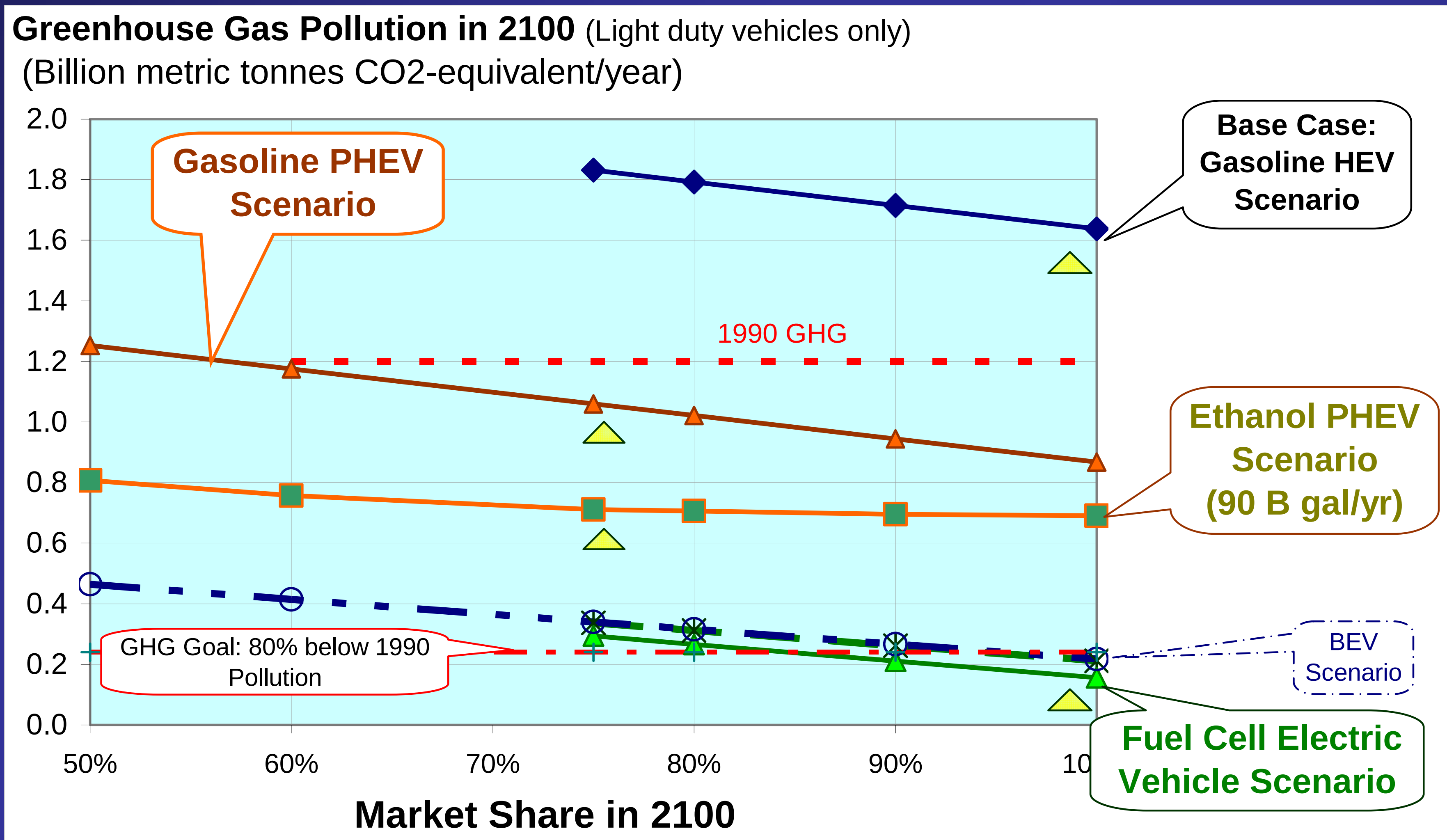
**Greenhouse Gas Pollution** (Light duty vehicles only)
(Billion/ tonnes CO2-equivalent/year)



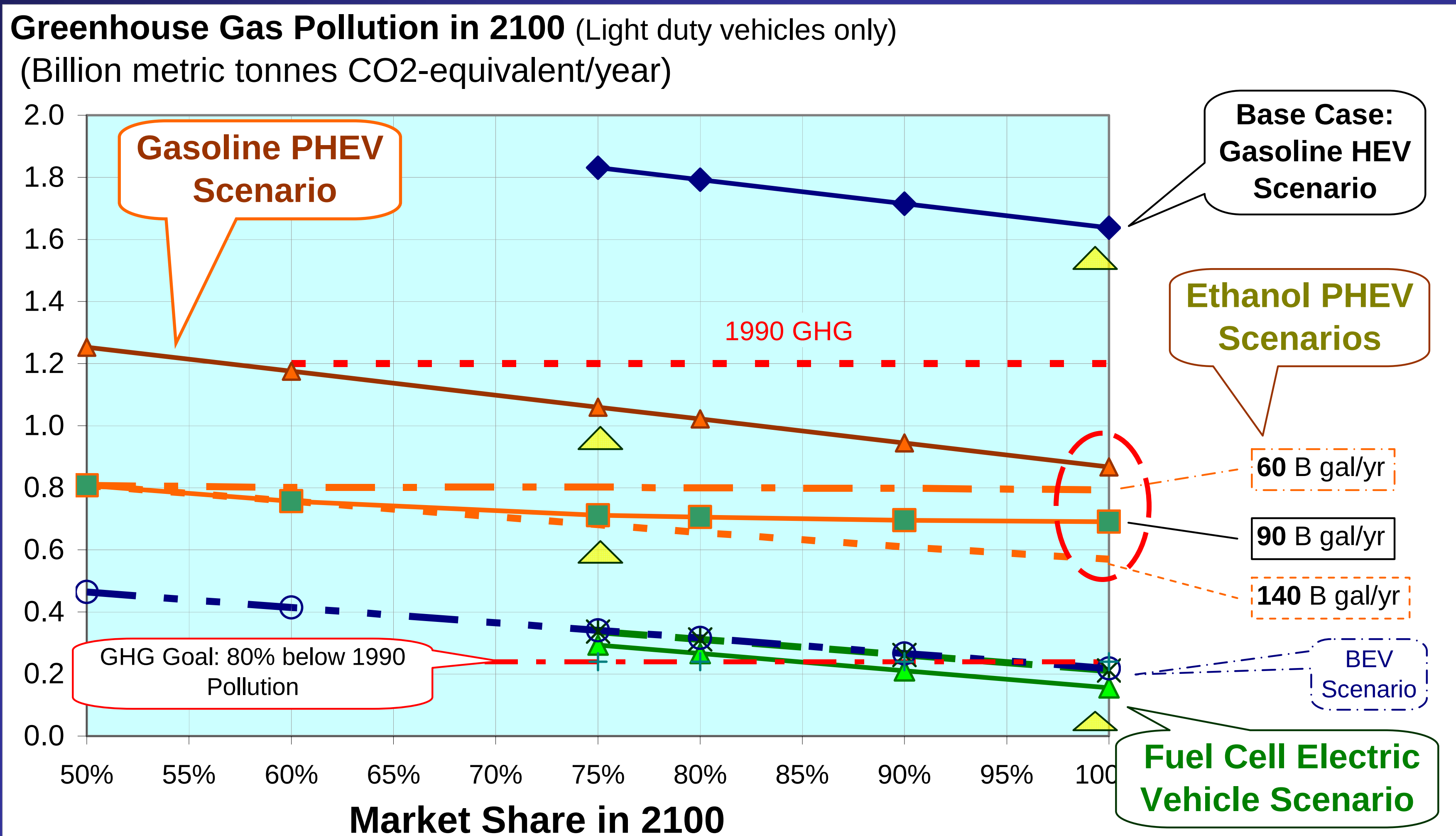



Graphs for Simultaneous Story.XLS; P 37 7/1 /2009

# GHG Sensitivity to Market Share



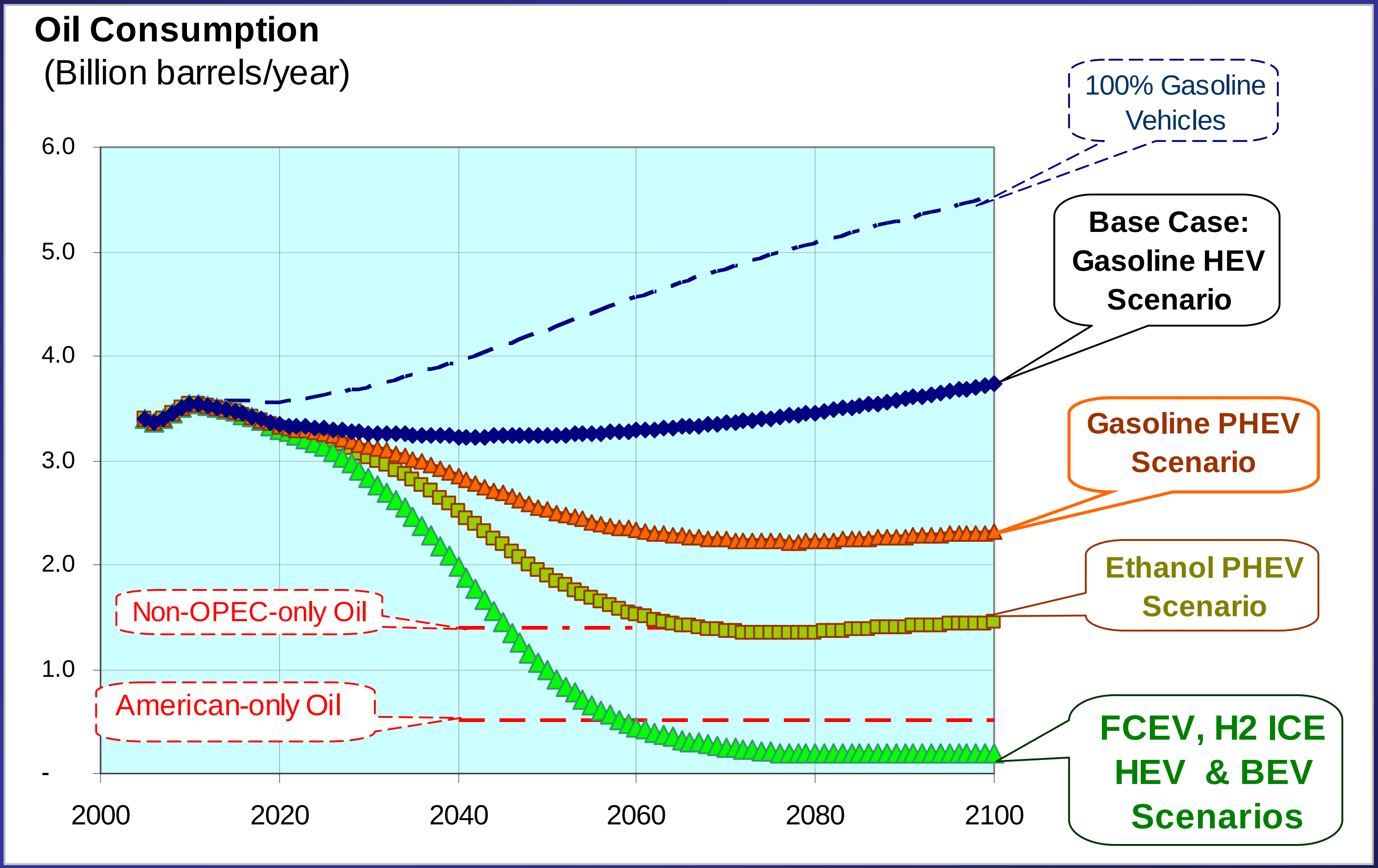
# GHG Sensitivity to Market Share & Ethanol Capacity






Story Simultaneous.XLS; Tab 'Sensitivity'; AB 201 7/1 /2009

# Oil Consumption

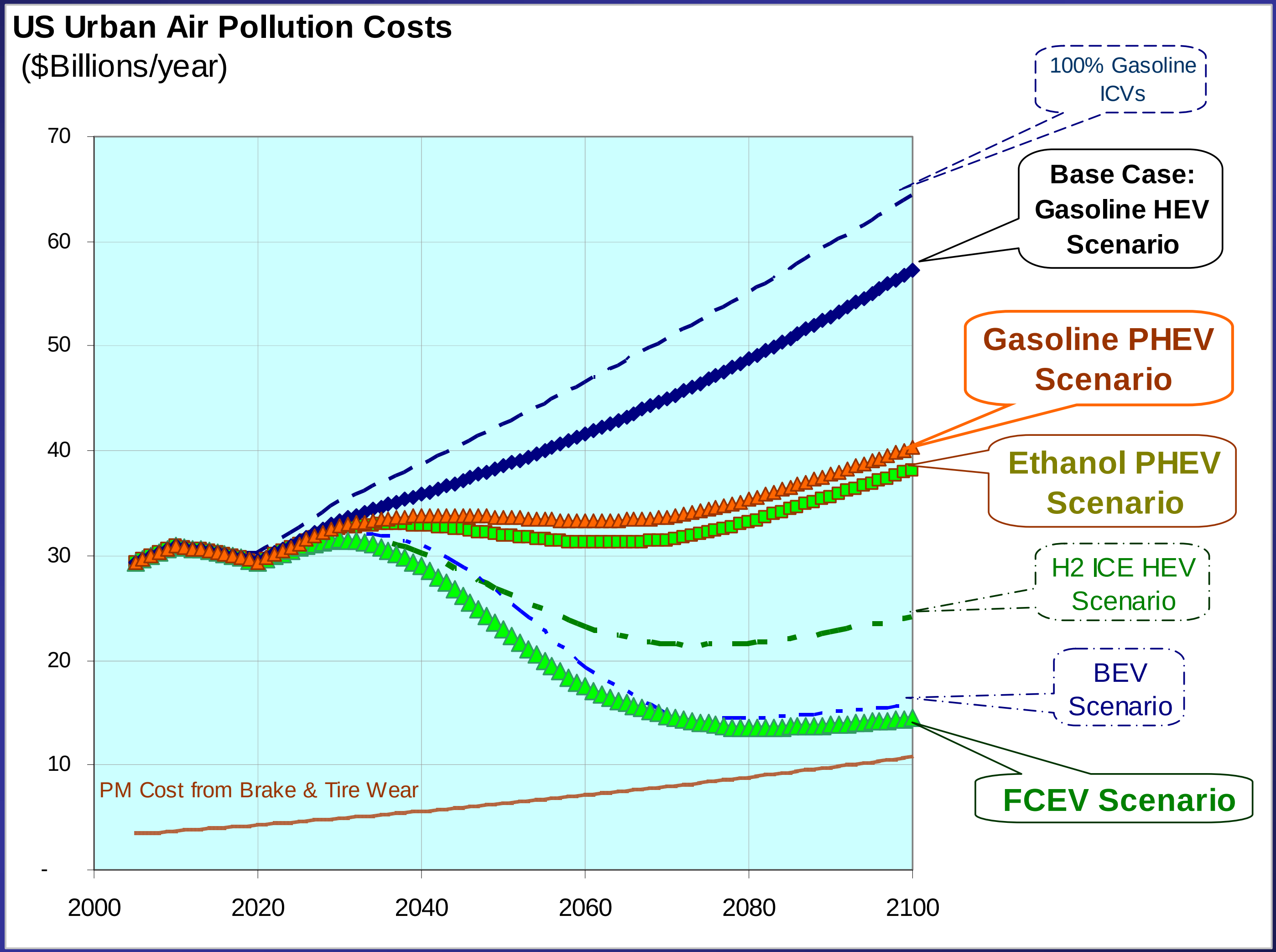





Sources: Argonne National Laboratory GREET 1.8a, AEO 2009 & NHA models

# Urban Air Pollution Costs

## (with H2 ICE HEVs and BEVs)




Sources: Argonne National Laboratory GREET 1.8a, AEO 2009 & NHA models

# Primary Conclusion

- Achieving GHG and Oil reduction targets will require all-electric vehicles*
- Two choices:
  - Battery EVs
  - Fuel Cell EVs *(with peak power battery)*
- Next slides will compare:
  - Mass
  - Volume
  - Greenhouse Gases
  - Cost

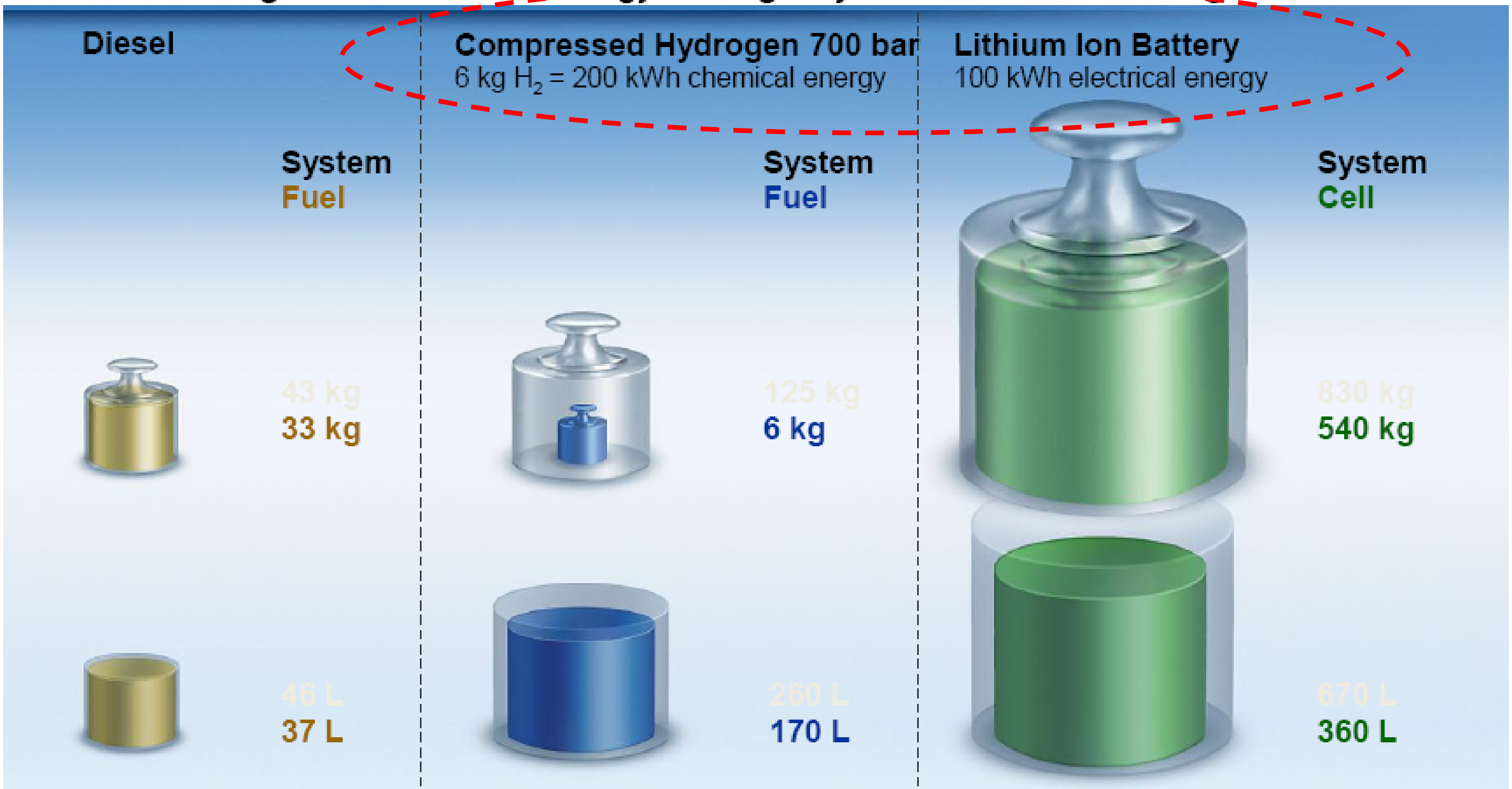


* Or Hydrogen ICE HEVs

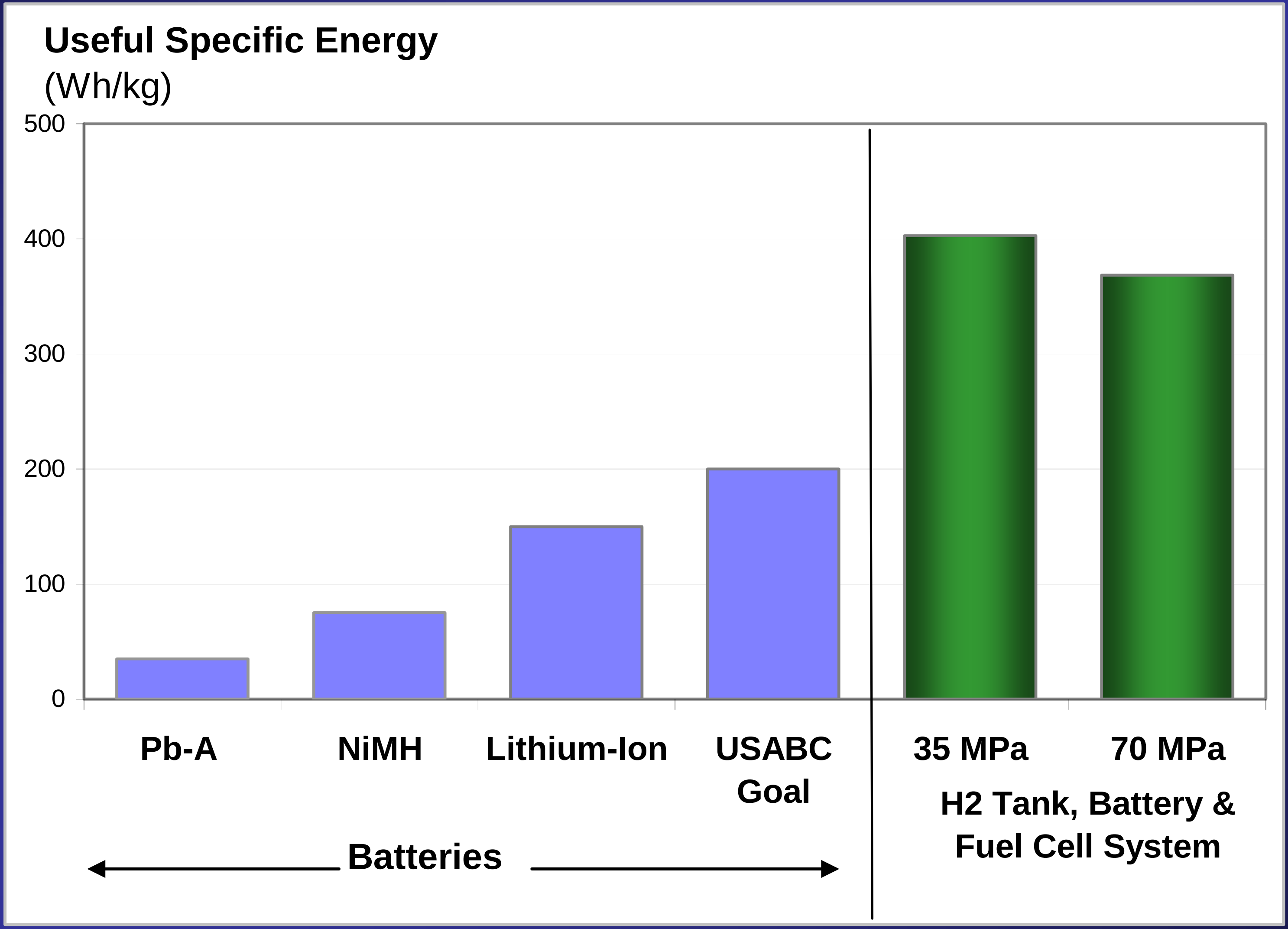
# Energy Carrier Properties: Onboard Storage

## Why is petroleum the dominant transportation fuel?

*Weight & Volume of Energy Storage System for 500 km Range*

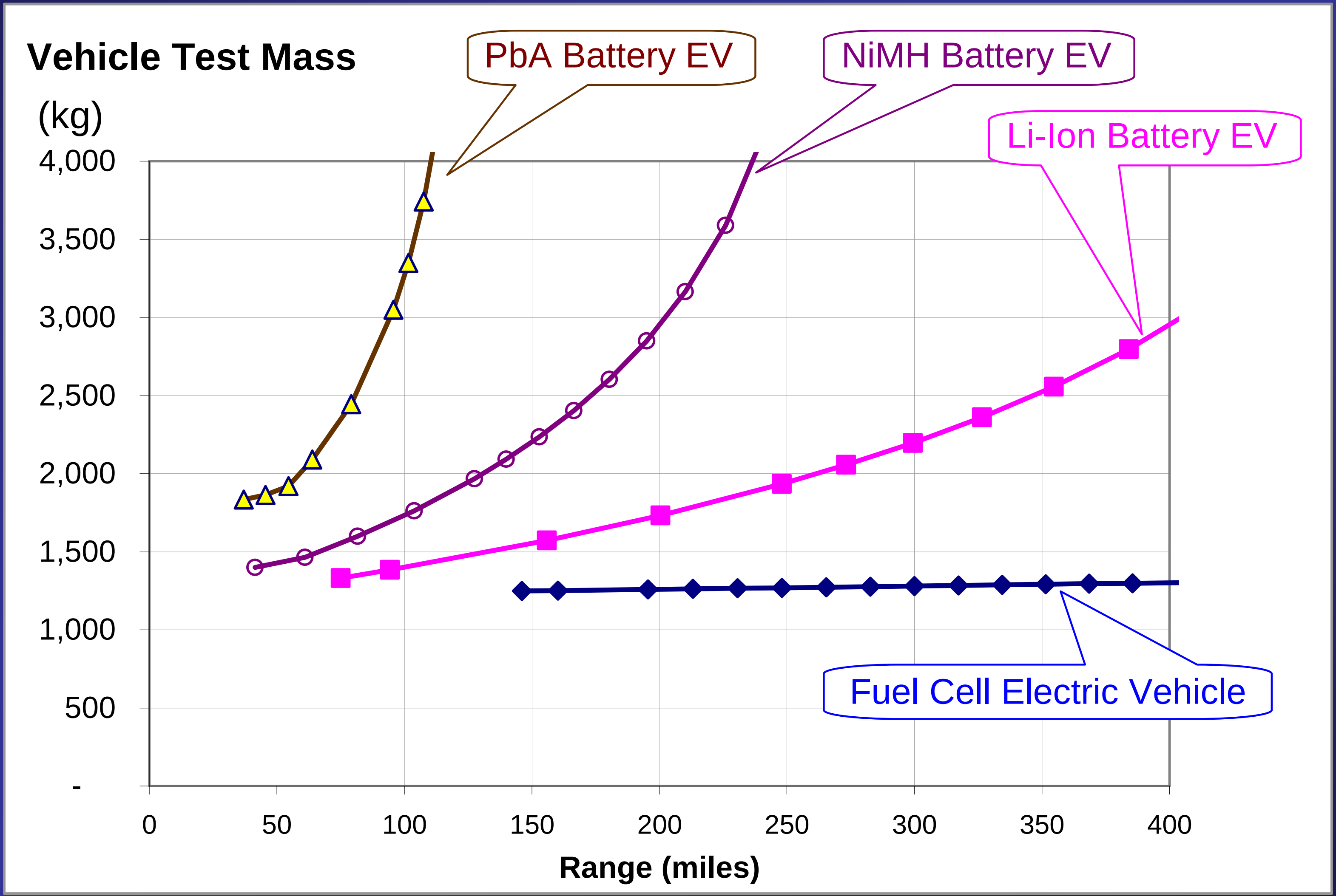


# Specific Energy Comparison



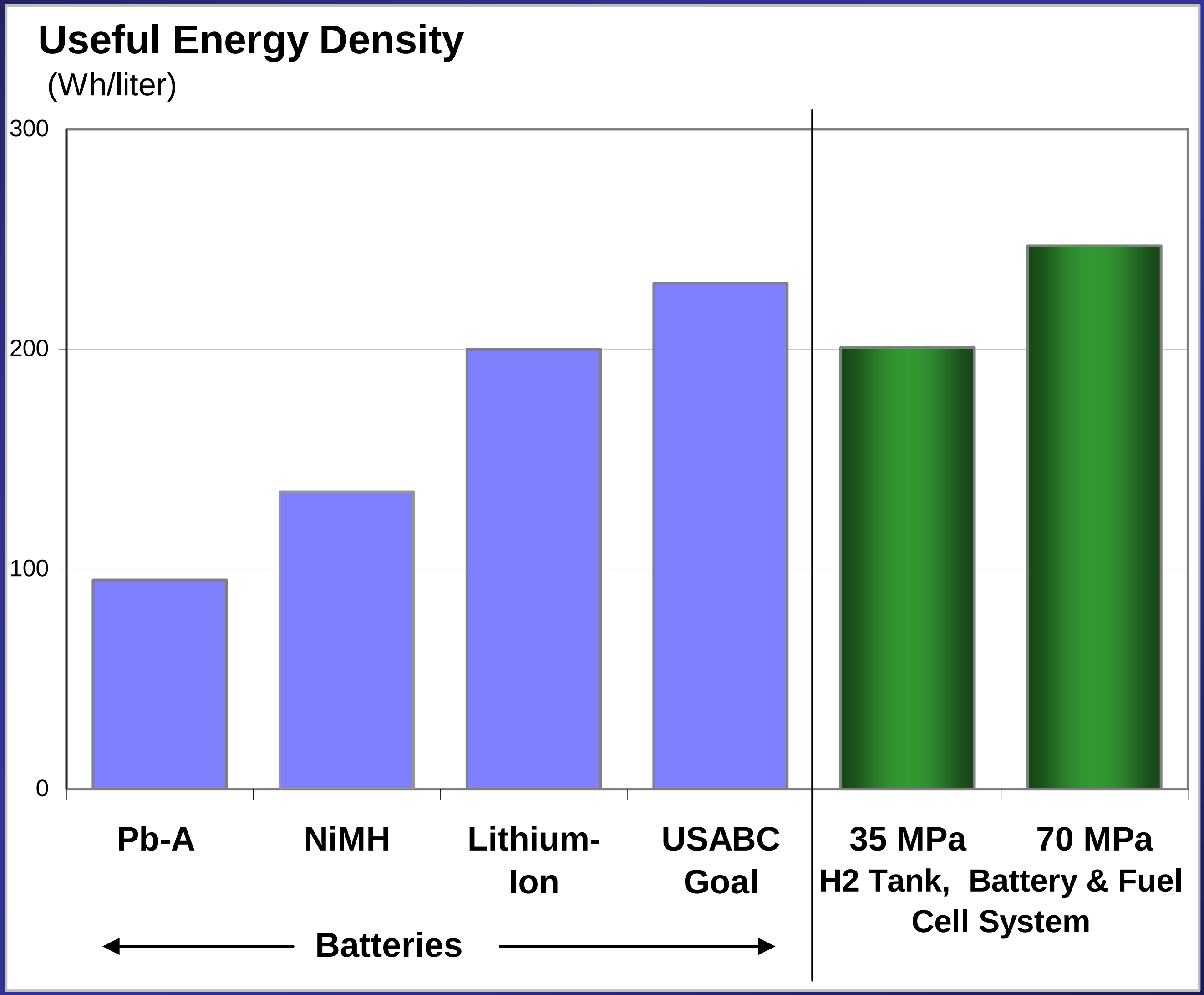
# Batteries Weigh More

(Effects of weight compounding)



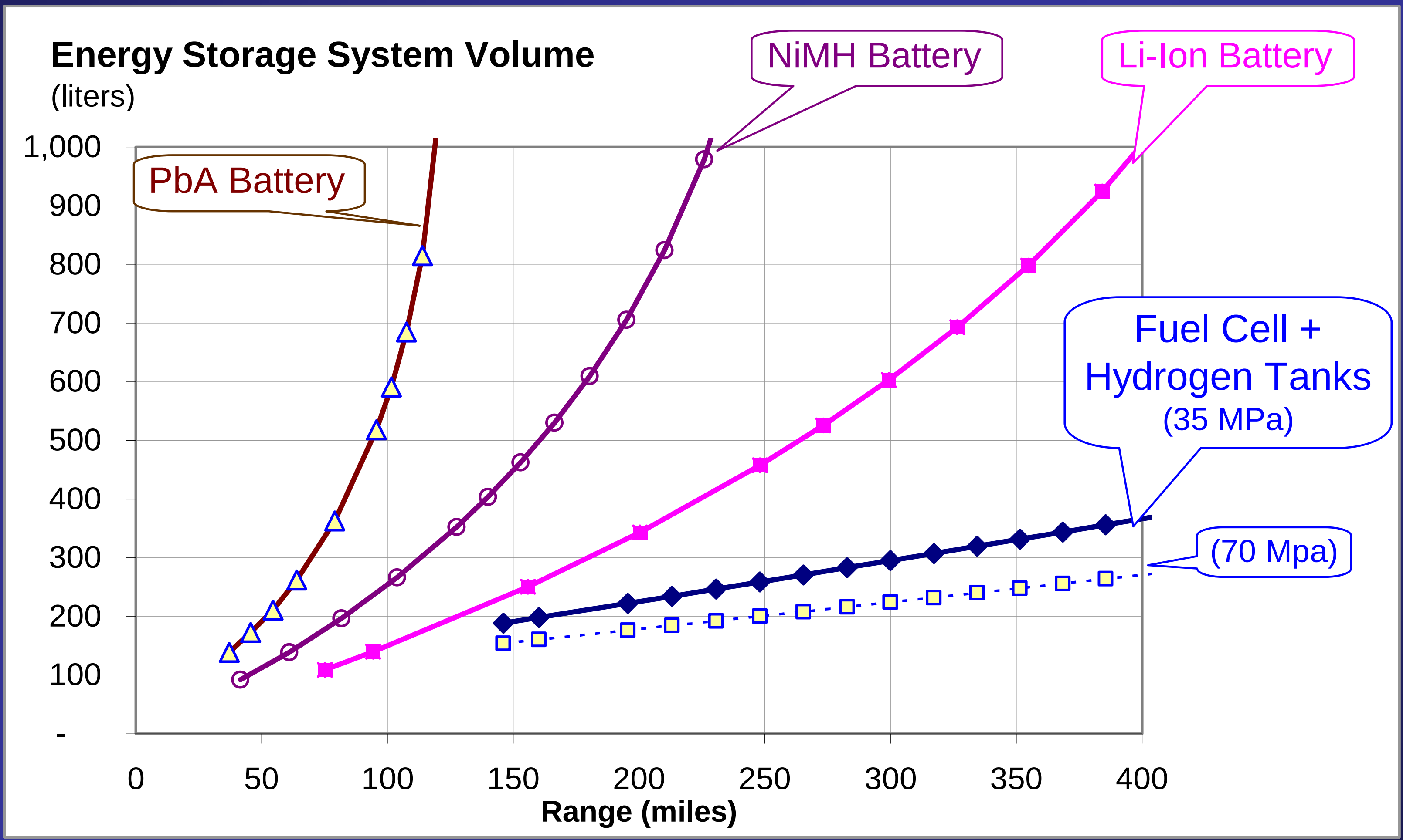

BPEV.XLS; 'Compound' AS146 5/13 /2009

# Useful Energy Density



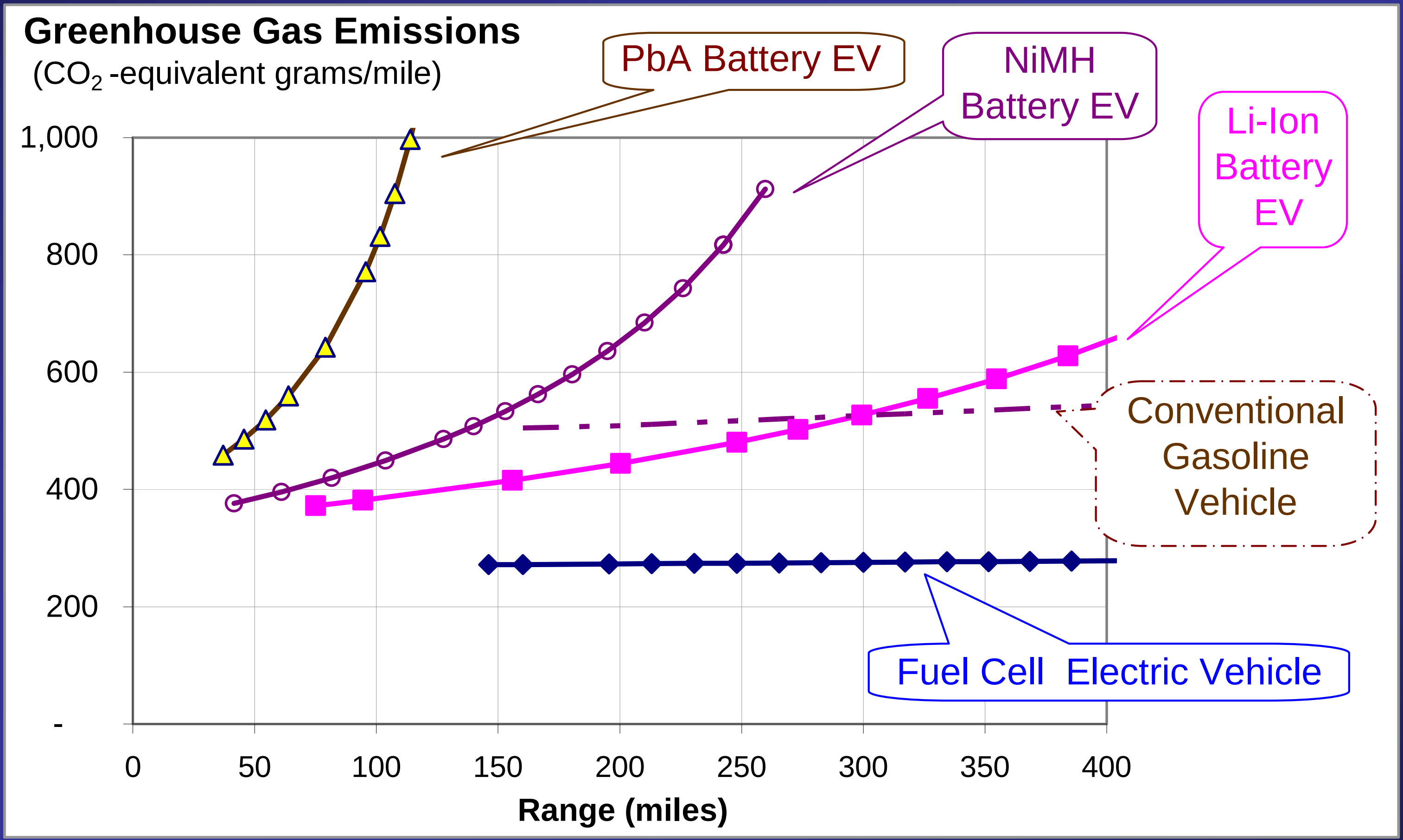

H2Gen: Wt_Vol_Cost.XLS; Tab 'Battery'; S36 - 7 / 1 / 2009

# Batteries also take up more space:




BPEV.XLS; 'Compound' AS113 5/13 /2009

# BEVs will initially generate more Greenhouse Gases than FCEVs*

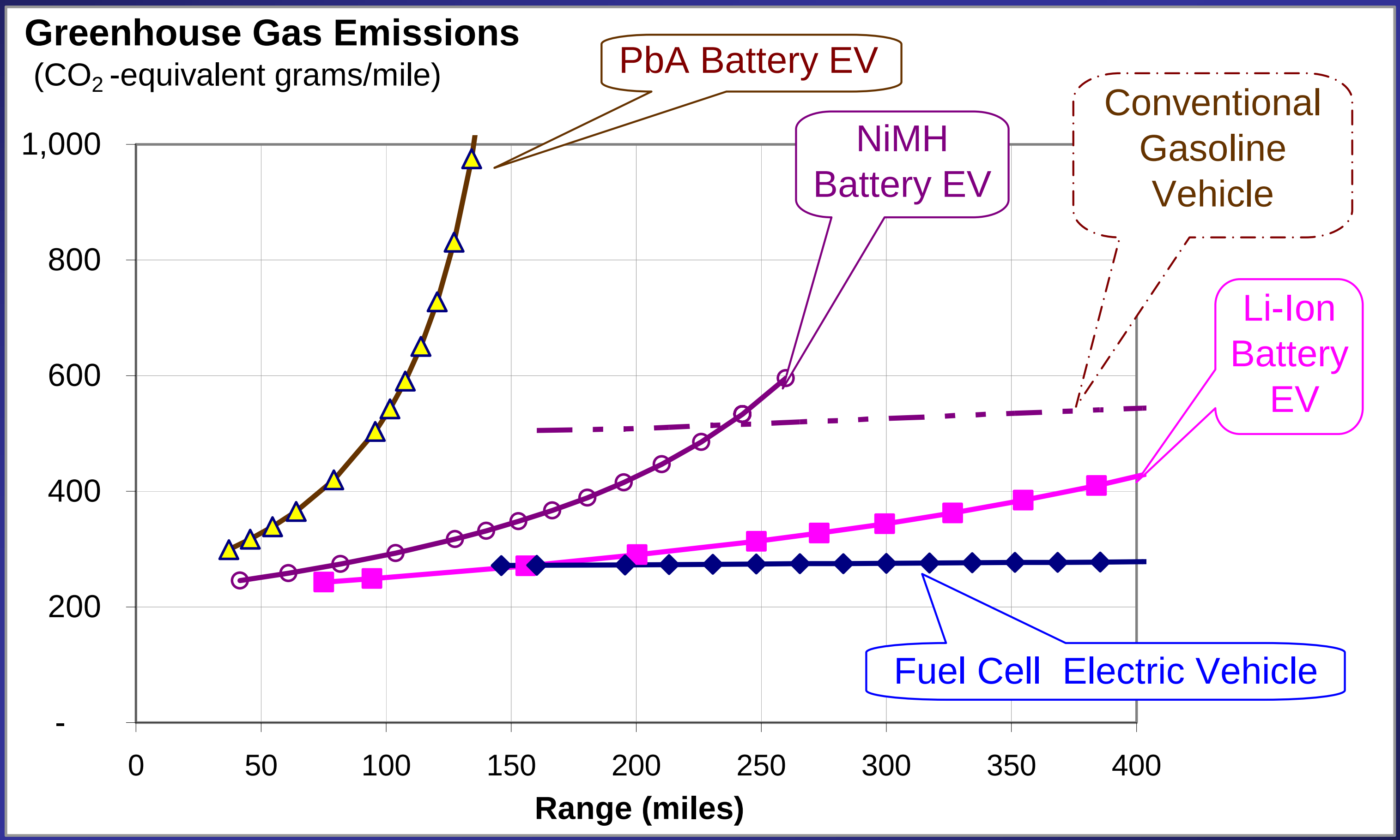



Grid Mix: US

BPEV.XLS; 'Compound' AQ200 5/13 /2009

*Assumes hydrogen made on-site from natural gas, and average marginal US electrical grid mix for charging EV batteries

# In California, GHGs for BEVs will initially be similar to FCEVs*

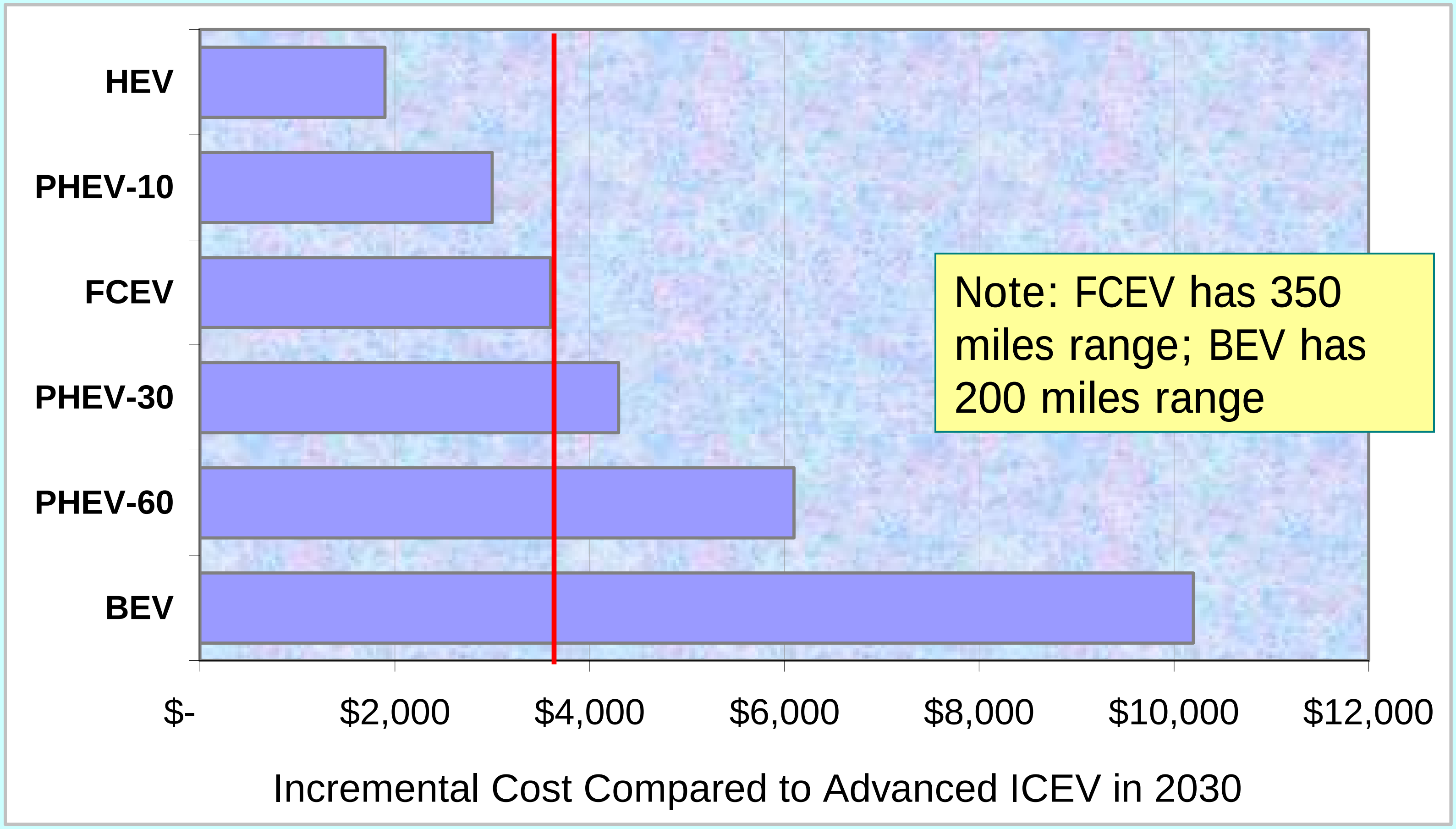



Grid Mix: California

BPEV.XLS; 'Compound' AQ200 5/13 /2009

*Assumes hydrogen made on-site from natural gas, and average marginal California electrical grid mix for charging EV batteries

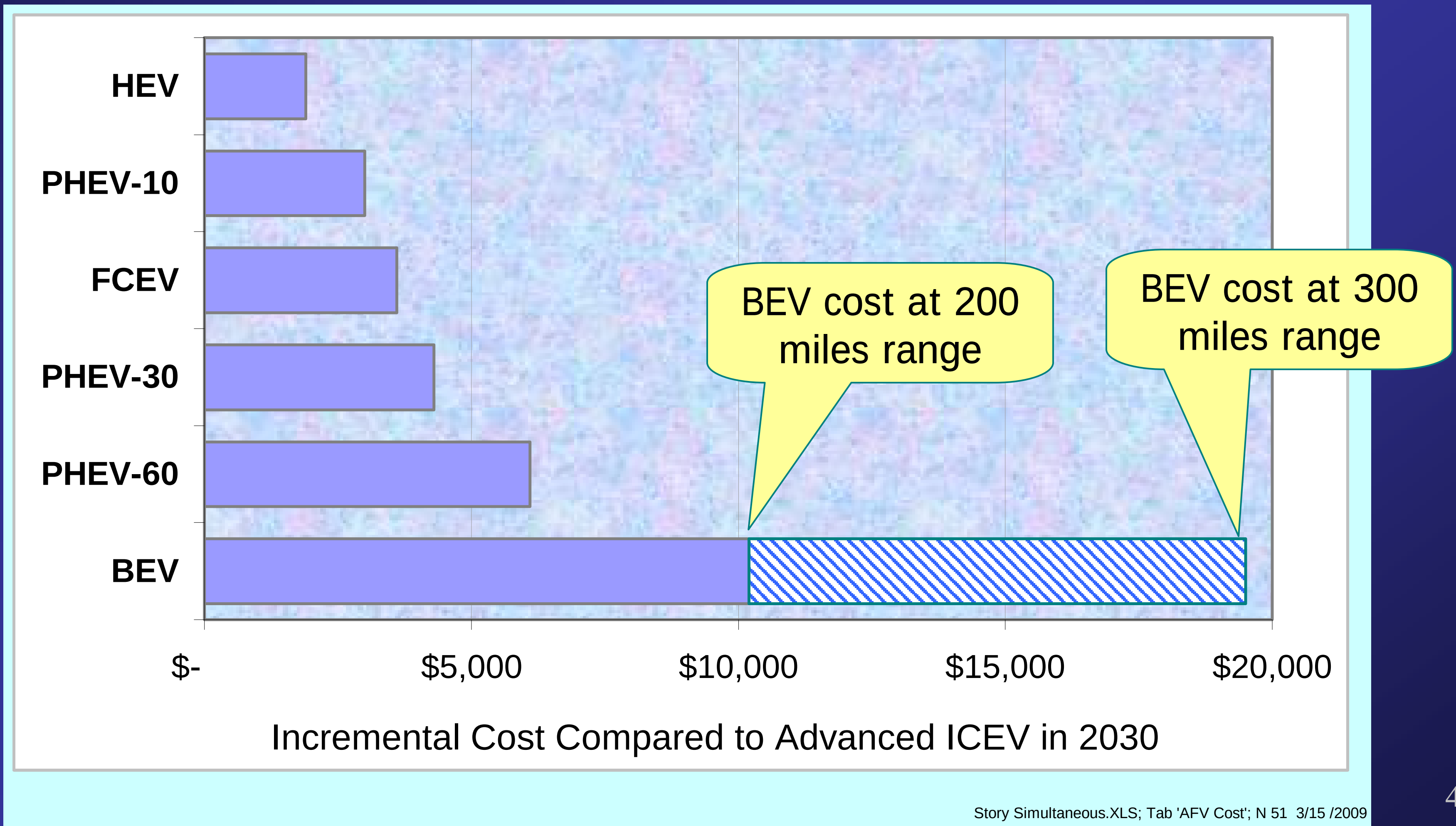
# ...and BEVs are projected to cost more than FCEVs by MIT (2030)




Ref: Kromer & Heywood, "Electric Powertrains: Opportunities & Challenges in the U.S. Light-Duty Vehicle Fleet Report # LFEE 2007-03RP, MIT, May, 2007, Table 53

Story Simultaneous.XLS; Tab 'AFV Cost'; N 26 3/15 /2009

# BEV cost estimate for 300 miles range (FCEV still at 350 miles range)




MIT assumes $250/kWh battery cost for BEVs ($600/kWh for HEVs)

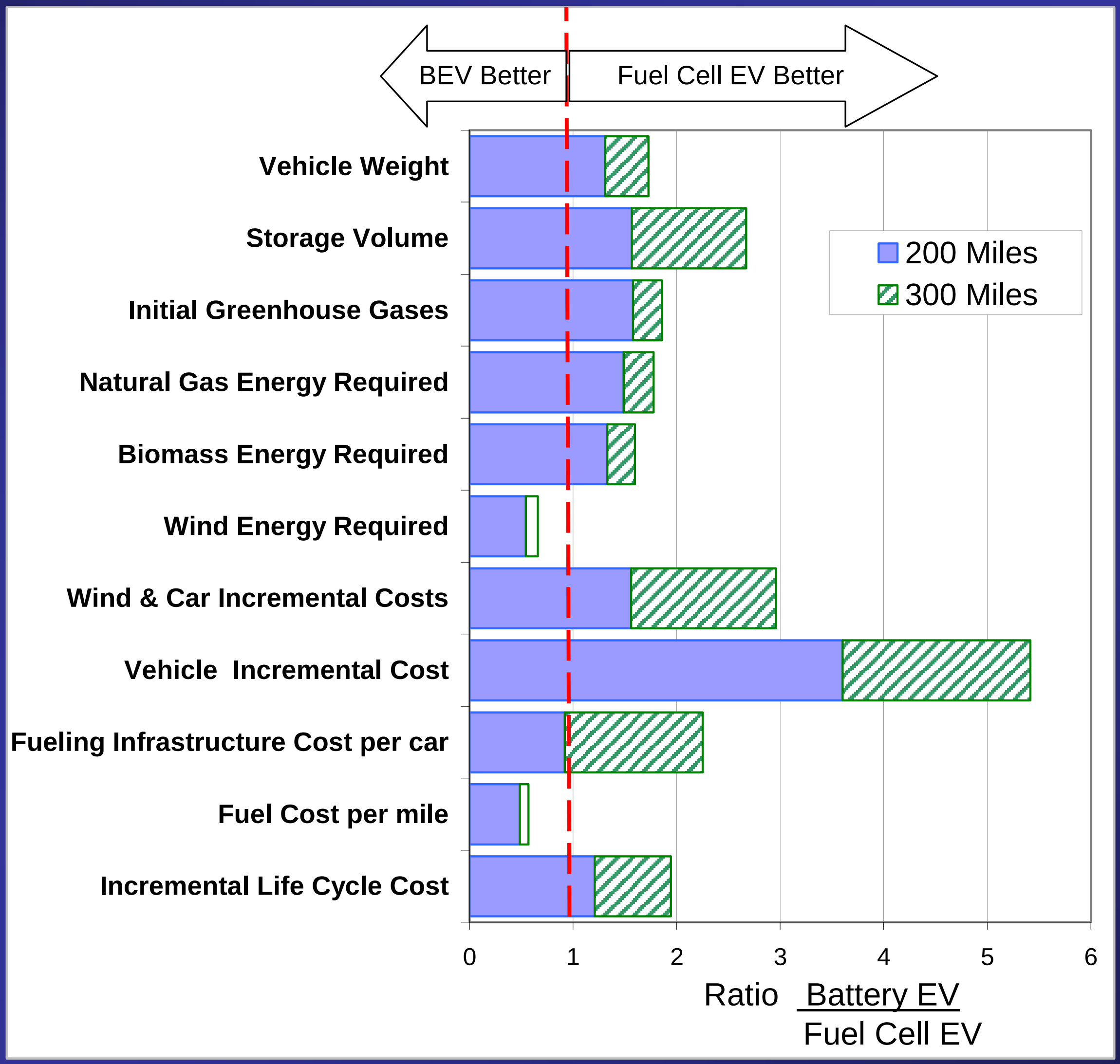
# Comparison of MIT Cost Assumptions & DOE Goals

| | | DOE 2010 | DOE 2015 | MIT 2030 |
|---|---|---|---|---|
| Fuel Cell System Cost | $/kW | 45 | 30 | 50 |
| Hydrogen Storage Cost | $/kWh | 4 | 2 | 15 |
| Hydrogen Storage Density | kWh/L | 0.9 | 1.3 | 0.8 |

Story Simultaneous.XLS; Tab 'AFV Cost'; E 33 3/19 /2009

If DOE goals were met, then the incremental cost for fuel cell electric vehicles would decrease from $3,600 estimated by MIT down to $840.

# Ratio Battery EV / Fuel Cell EV




Story Simultaneous.XLS; Tab 'AFV Cost'; Z 124 4/30 /2009

H2Gen

# Composite Comparison Chart

(Normalized to Baseline Gasoline Hybrid Electric Vehicle)

| | Plug-in Hybrid Electric Vehicle (PHEV) | | Battery Electric Vehicle (BEV) | Fuel Cell Electric Vehicle (FCEV) |
|---|---|---|---|---|
| | Gasoline PHEV | Ethanol-PHEV | | |
| Vehicle Mass Production Cost | 124.0% | 124.0% | 197.5% | 118.0% |
| Annual Fuel Cost | 49.0% | 49.0% | 20.3% | 52.0% |

Graphs for Simultaneous Story.XLS; Tab 'R-Y-G Chart'; N 117 7/2 /2009

# Composite Comparison Chart

(Normalized to Baseline Gasoline Hybrid Electric Vehicle)

| | Plug-in Hybrid Electric Vehicle (PHEV) | | Battery Electric Vehicle (BEV) | Fuel Cell Electric Vehicle (FCEV) |
|---|---|---|---|---|
| | Gasoline PHEV | Ethanol-PHEV | | |
| Vehicle Mass Production Cost | 124.0% | 124.0% | 197.5% | 118.0% |
| Annual Fuel Cost | 49.0% | 49.0% | 20.3% | 52.0% |
| Life Cycle Cost | 83.1% | 83.1% | 100.8% | 82.0% |

# Composite Comparison Chart

(Normalized to Baseline Gasoline Hybrid Electric Vehicle)

| | Plug-in Hybrid Electric Vehicle (PHEV) | | Battery Electric Vehicle (BEV) | Fuel Cell Electric Vehicle (FCEV) |
|---|---|---|---|---|
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| Vehicle Mass Production Cost | 124.0% | 124.0% | 197.5% | 118.0% |
| Annual Fuel Cost | 49.0% | 49.0% | 20.3% | 52.0% |
| Life Cycle Cost | 83.1% | 83.1% | 100.8% | 82.0% |
| | 2020 | 2020 | 2020 | 2020 |
| Greenhouse Gases | 98.9% | 66.7% | 154.0% | 61.2% |
| Oil Consumption | 77.3% | 20.6% | 1.5% | 1.4% |
| Urban Air Pollution | 90.2% | 78.9% | 82.9% | 65.1% |
| Societal Costs | 82.3% | 35.4% | 35.4% | 19.0% |

Graphs for Simultaneous Story.XLS; Tab 'R-Y-G Chart'; N 117 7/2 /2009

# Composite Comparison Chart

(Normalized to Baseline Gasoline Hybrid Electric Vehicle)

| | Plug-in Hybrid Electric Vehicle (PHEV) | | | | Battery Electric Vehicle (BEV) | | Fuel Cell Electric Vehicle (FCEV) | |
|---|---|---|---|---|---|---|---|---|
| | Gasoline PHEV | | Ethanol-PHEV | | | | | |
| Vehicle Mass Production Cost | 124.0% | | 124.0% | | 197.5% | | 118.0% | |
| Annual Fuel Cost | 49.0% | | 49.0% | | 20.3% | | 52.0% | |
| Life Cycle Cost | 83.1% | | 83.1% | | 100.8% | | 82.0% | |
| | 2020 | 2050 | 2020 | 2050 | 2020 | 2050 | 2020 | 2050 |
| Greenhouse Gases | 98.9% | 83.6% | 66.7% | 41.4% | 154.0% | 89.3% | 61.2% | 27.3% |
| Oil Consumption | 77.3% | 61.9% | 20.6% | 16.0% | 1.5% | 1.3% | 1.4% | 2.0% |
| Urban Air Pollution | 90.2% | 77.4% | 78.9% | 67.7% | 82.9% | 54.5% | 65.1% | 36.2% |
| Societal Costs | 82.3% | 68.1% | 35.4% | 28.3% | 35.4% | 25.1% | 19.0% | 11.6% |

Graphs for Simultaneous Story.XLS; Tab 'R-Y-G Chart'; N 117 7/2 /2009

# Composite Comparison Chart

(Normalized to Baseline Gasoline Hybrid Electric Vehicle)

| | Plug-in Hybrid Electric Vehicle (PHEV) | | | | | | Battery Electric Vehicle (BEV) | | | Fuel Cell Electric Vehicle (FCEV) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gasoline PHEV | | | Ethanol-PHEV | | | | | | | | |
| Vehicle Mass Production Cost | 124.0% | | | 124.0% | | | 197.5% | | | 118.0% | | |
| Annual Fuel Cost | 49.0% | | | 49.0% | | | 20.3% | | | 52.0% | | |
| Life Cycle Cost | 83.1% | | | 83.1% | | | 100.8% | | | 82.0% | | |
| | 2020 | 2050 | 2100 | 2020 | 2050 | 2100 | 2020 | 2050 | 2100 | 2020 | 2050 | 2100 |
| Greenhouse Gases | 98.9% | 83.6% | 50.9% | 66.7% | 41.4% | 19.0% | 154.0% | 89.3% | 11.4% | 61.2% | 27.3% | 6.4% |
| Oil Consumption | 77.3% | 61.9% | 47.1% | 20.6% | 16.0% | 12.2% | 1.5% | 1.3% | 0.9% | 1.4% | 2.0% | 1.9% |
| Urban Air Pollution | 90.2% | 77.4% | 59.3% | 78.9% | 67.7% | 53.7% | 82.9% | 54.5% | 26.2% | 65.1% | 36.2% | 22.4% |
| Societal Costs | 82.3% | 68.1% | 50.0% | 35.4% | 28.3% | 20.6% | 35.4% | 25.1% | 7.4% | 19.0% | 11.6% | 6.3% |

Graphs for Simultaneous Story.XLS; Tab 'R-Y-G Chart'; N 117 7/2 /2009

# Economic Projections

- Fueling infrastructure cost:
  – ICE PHEV fueling
  – FC HEV fueling
- Cash flow for hydrogen fueling industry
- Cash flow for fuel cell vehicle owners
  – Vehicle incremental cost
  – Hydrogen fuel savings

# ICE PHEV "Fueling Infrastructure" Cost per Car

- Average residential electrical outlet cost:
  - $878 for Level I (120V, 20A, 1.9 kW)
  - $2,150 for Level II (240 V, 40 A, 7.9 kW)
- Commercial Level II outlet: $1,850
- Infrastructure cost per car: $900 to $2,000 *[paid up-front by driver for home refueling]*

[Source: Morrow, Idaho National Laboratory, November 2008]

# FC HEV Fueling Infrastructure Cost per Car

- NRC 1,500 kg/day fueling station cost in 500 quantity production: $2.2 million
- NHA estimate: $2.9 million
- Serving 2,300 FCEVs*
- Average cost per FCEV: $955 to $1,260

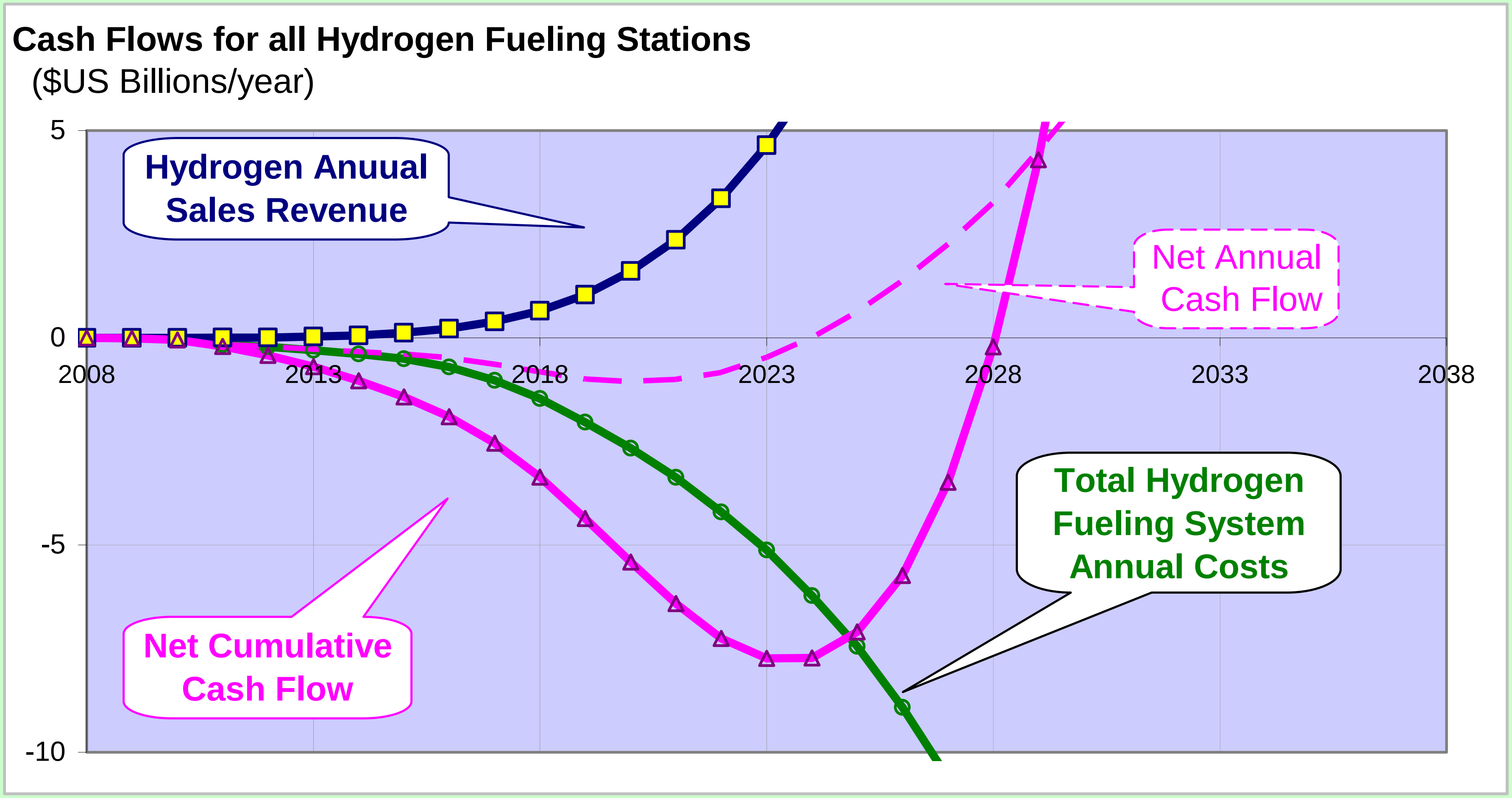
*[paid by fuel provider]*

| Capacity | Fueling Station Costs | | NRC |
|---|---|---|---|
| | Single Qty | 500 Qty | 500 Qty |
| 100 kg/day | $ 772,800 | $ 535,000 | $ 397,000 |
| 500 kg/day | $ 2,212,000 | $ 1,534,000 | $ 905,500 |
| 1,500 kg/day | $ 4,181,700 | $ 2,900,000 | $ 2,178,000 |

H2 Energy Story.XLS; Tab 'Annual Sales';EC 18 5/15 /2009

*Assumes 4.5 kg to travel 350 miles, 70% average fueling station capacity factor, and 13,000 miles traveled per year

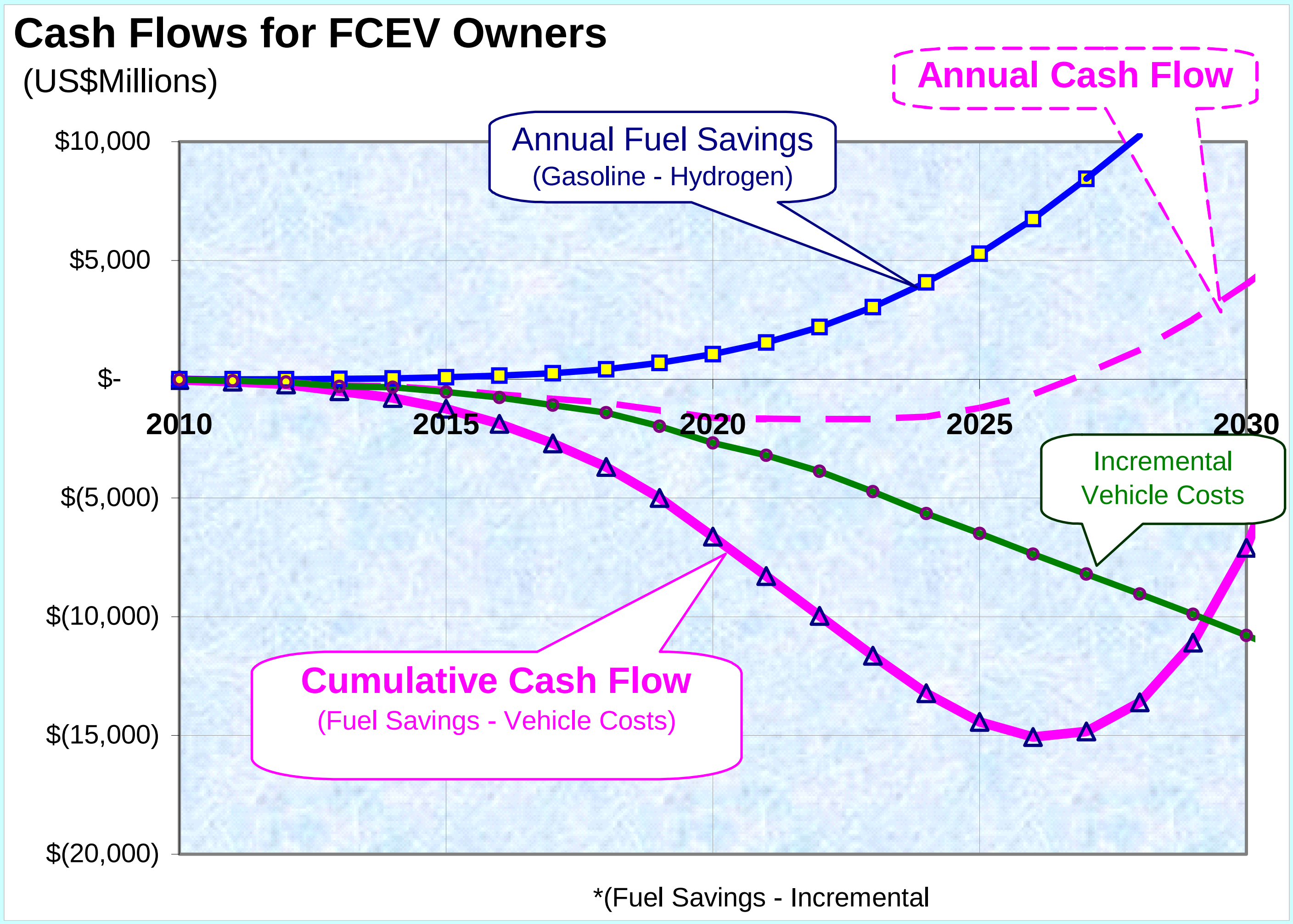
# Hydrogen Fueling Industry




Hydrogen Price set at 55% of gasoline price per mile

Story Simultaneous.XLS; Tab 'H2 Cost';AG 82 5/15 /2009

# Fuel Cell Vehicle Owners



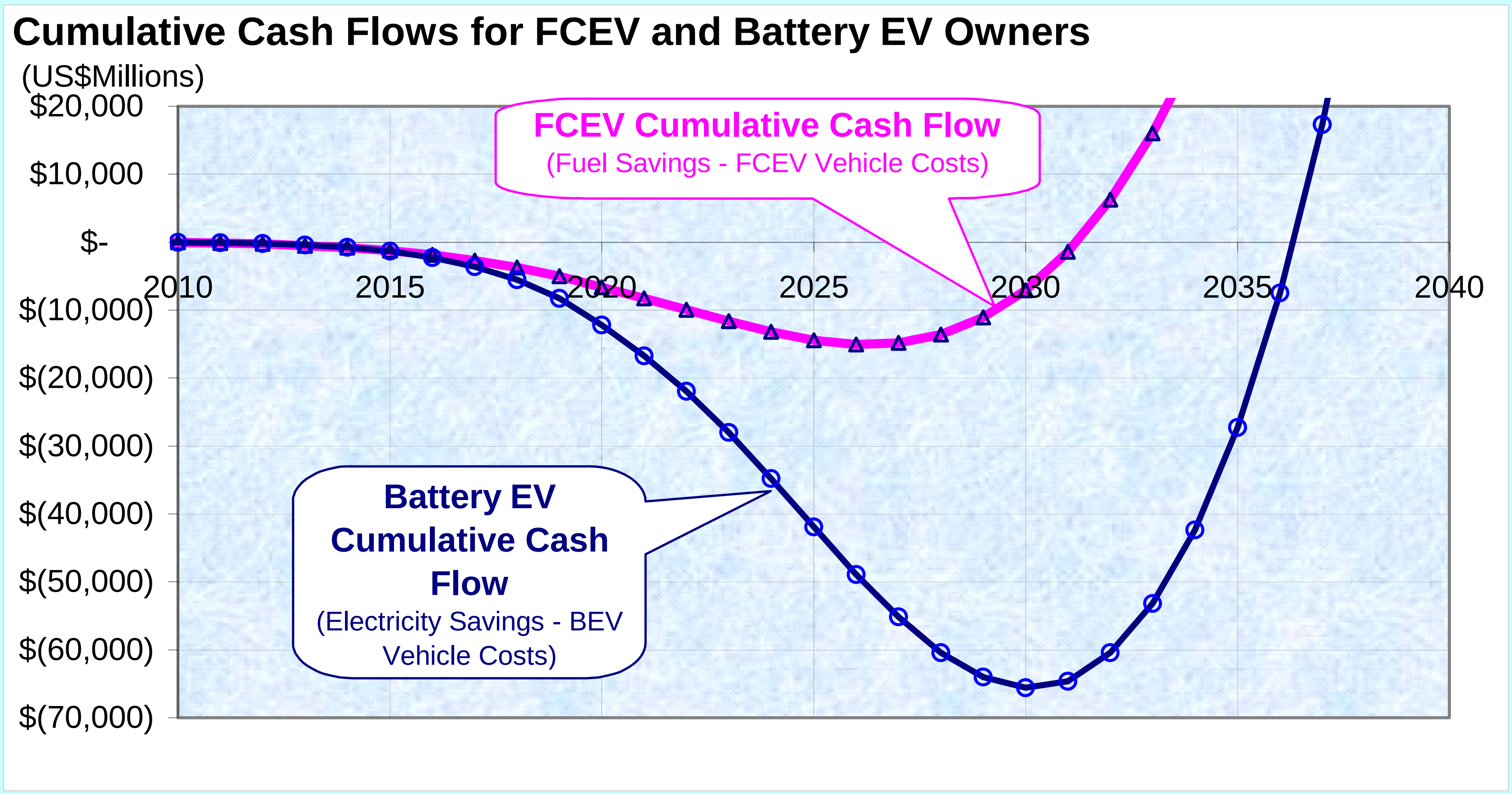

FCEV& BEV Premium Paid = $ 1,000

Story Simultaneous.XLS; Tab 'Driver'; K 24 5/15 /2009

Fuel Savings Derating Factor = 0.80

H2 Price as fraction of gasoline price: 55%

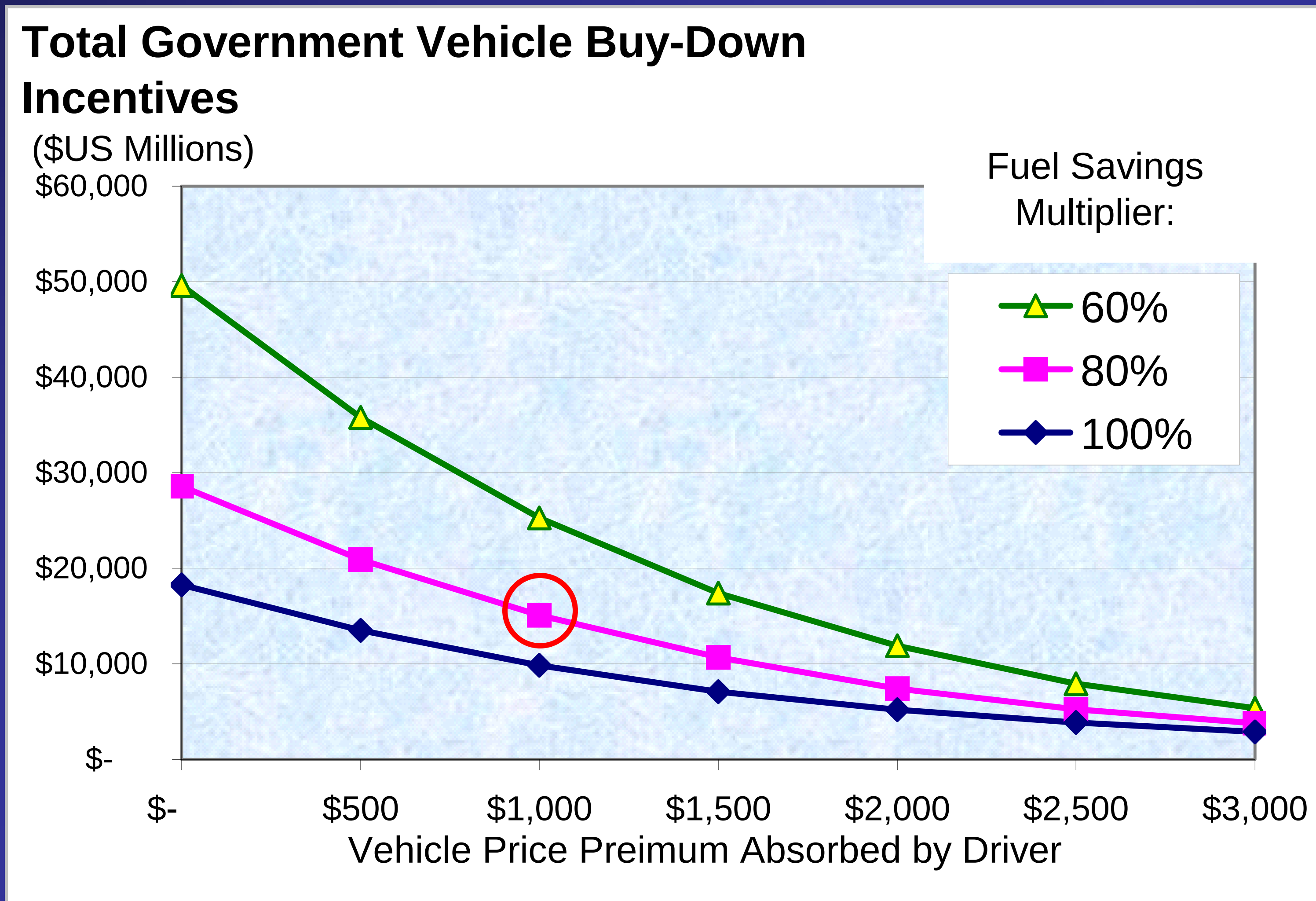
# Incentives Required for Battery EVs and Fuel Cell EVs




| | | | | |
|---|---|---|---|---|
| Vehicle Premium: | $ | 1,000 | Off-Peak Electricity (% of On-Peak) = | 55% |
| Fuel Fraction | | 0.80 | H2 Price (% of Gasoline per mile) = | 55% |

taneous.XLS; Tab 'Driver'; BE 23 5/15 /2009

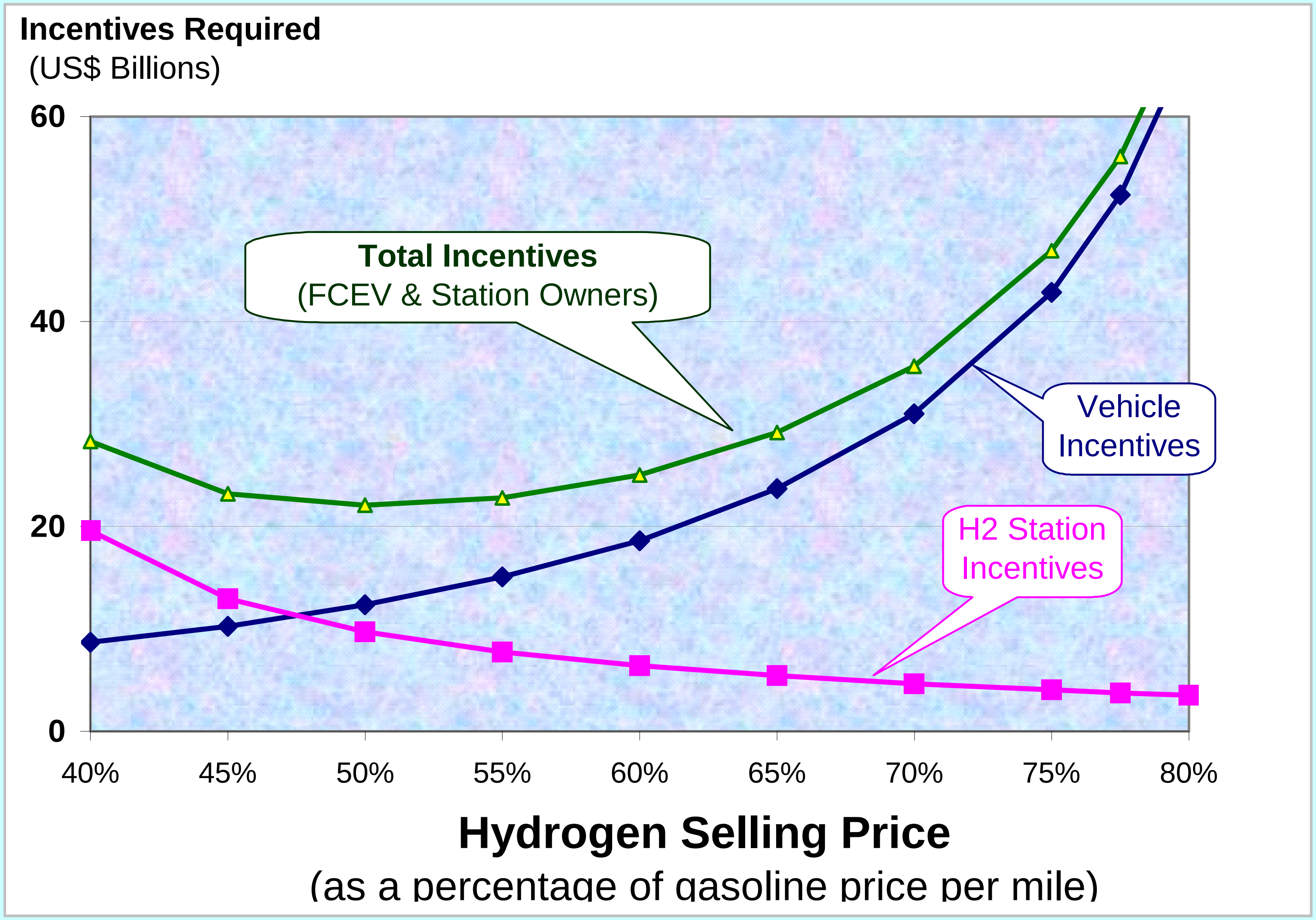
# Vehicle Buy-Down Incentives Required






Story Simultaneous.XLS; Tab 'Driver'; AW 25 5/15 /2009

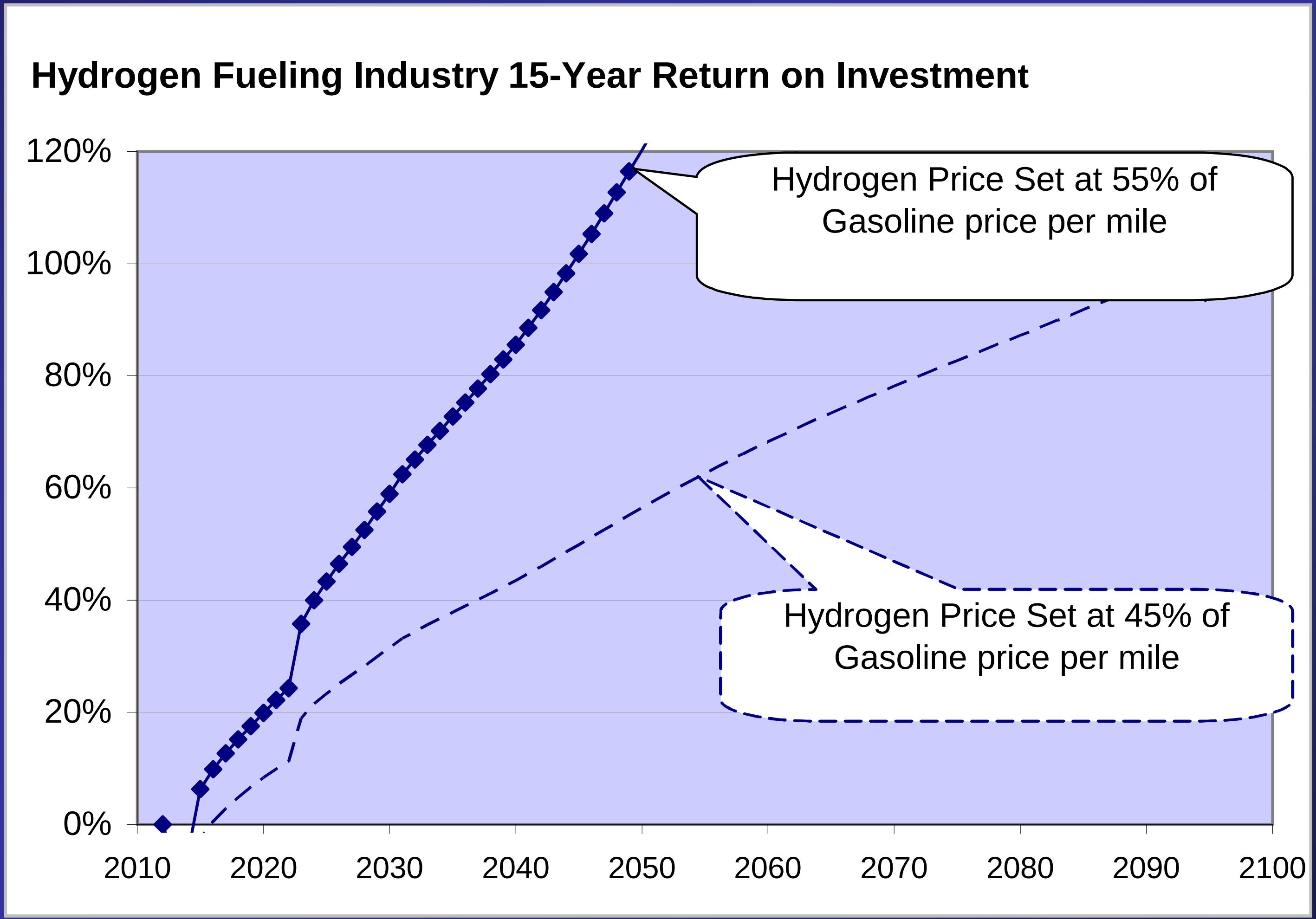
# Incentives Required




FCEV& BEV Premium Paid = $ 1,000
Fuel Savings Derating Factor = 0.80

Story Simultaneous.XLS; Tab 'H2 Cost'; BT 126 5/15 /2009

# Can fueling station owners profit from selling hydrogen at 55% discount?






Story Simultaneous.XLS; Tab 'H2 Cost';AP 55 5/15 /2009

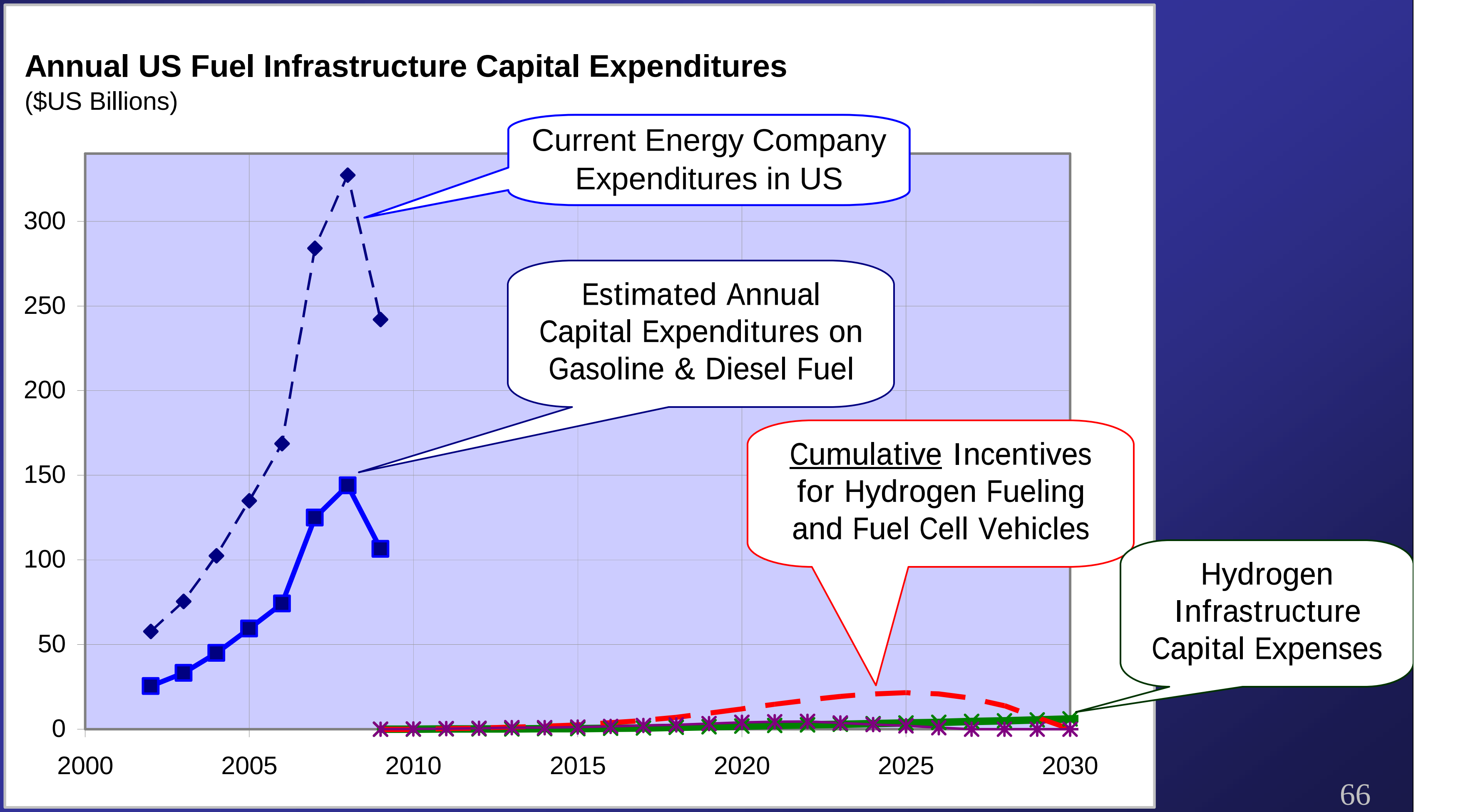
# Net Cumulative Incentives Required

- For hydrogen fueling industry: $9 billion
- For fuel cell vehicle owners: $15 billion

- Total private and government investment required: **$24 billion** over 14 years (2010 through 2024)

# H2 Infrastructure Costs & Required Incentives

(Compared to Gasoline & Diesel Infrastructure Costs)




H2 Energy Story.XLS; Tab 'Annual Sales';ID 146 5/13 /2009

Source: Oil & Gas Journal, April 2009

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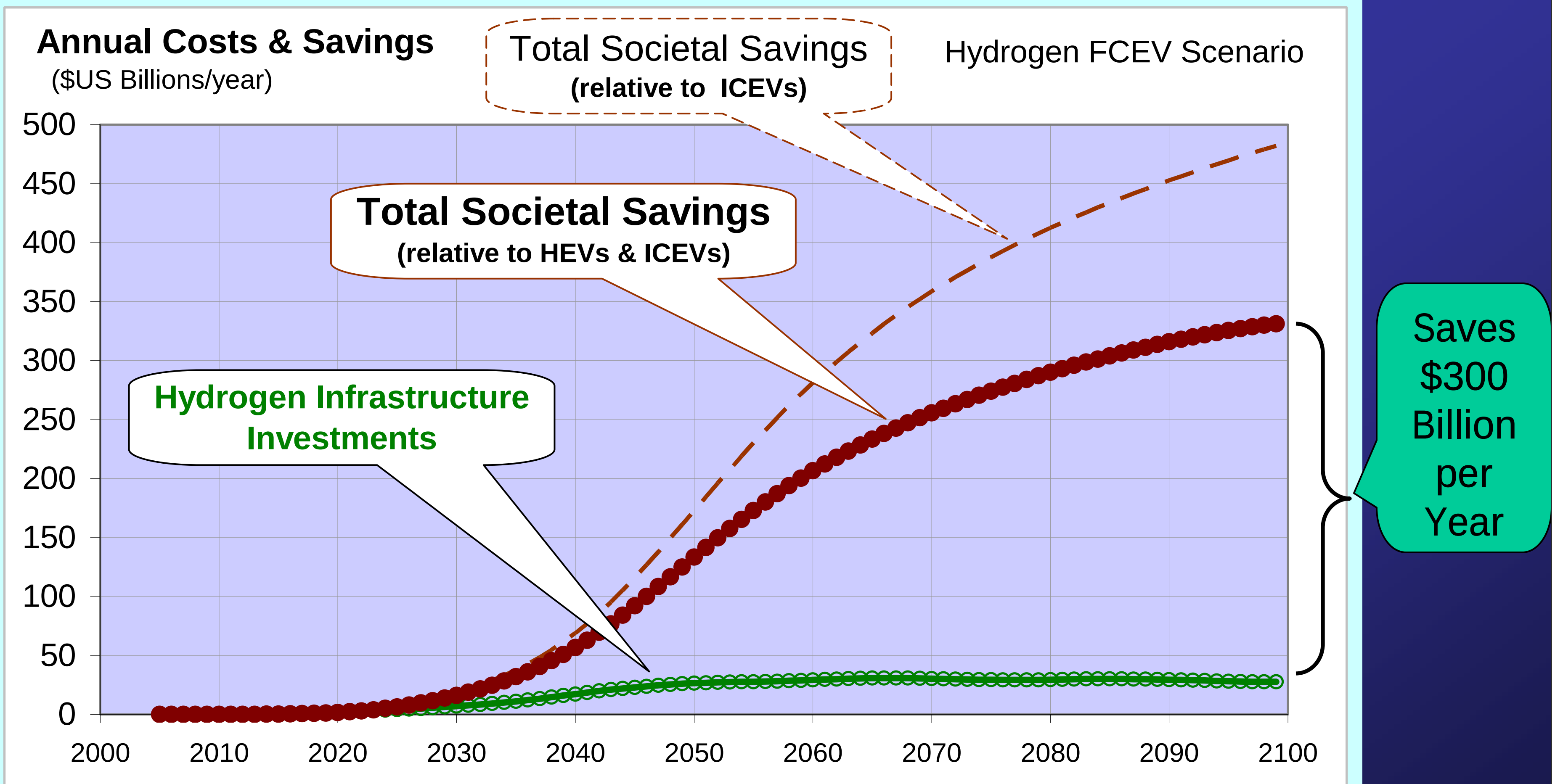
# $H_2$ Costs & Societal Savings




| | PM-10 | PM-2.5 | SOx | VOC | CO | NOx | CO2 |
|---|---|---|---|---|---|---|---|
| **Costs of Pollution:** | 1,608 | 134,041 | 29,743 | 6,592 | 1,276 | 13,844 | 25 to 50 |
| ($/metric tonne) | | **Crude Oil Economic Cost** | | **$60/bbl** | | | |

H2 Energy Story.XLS; Tab 'Annual Sales';FL 26 2/18 /2009

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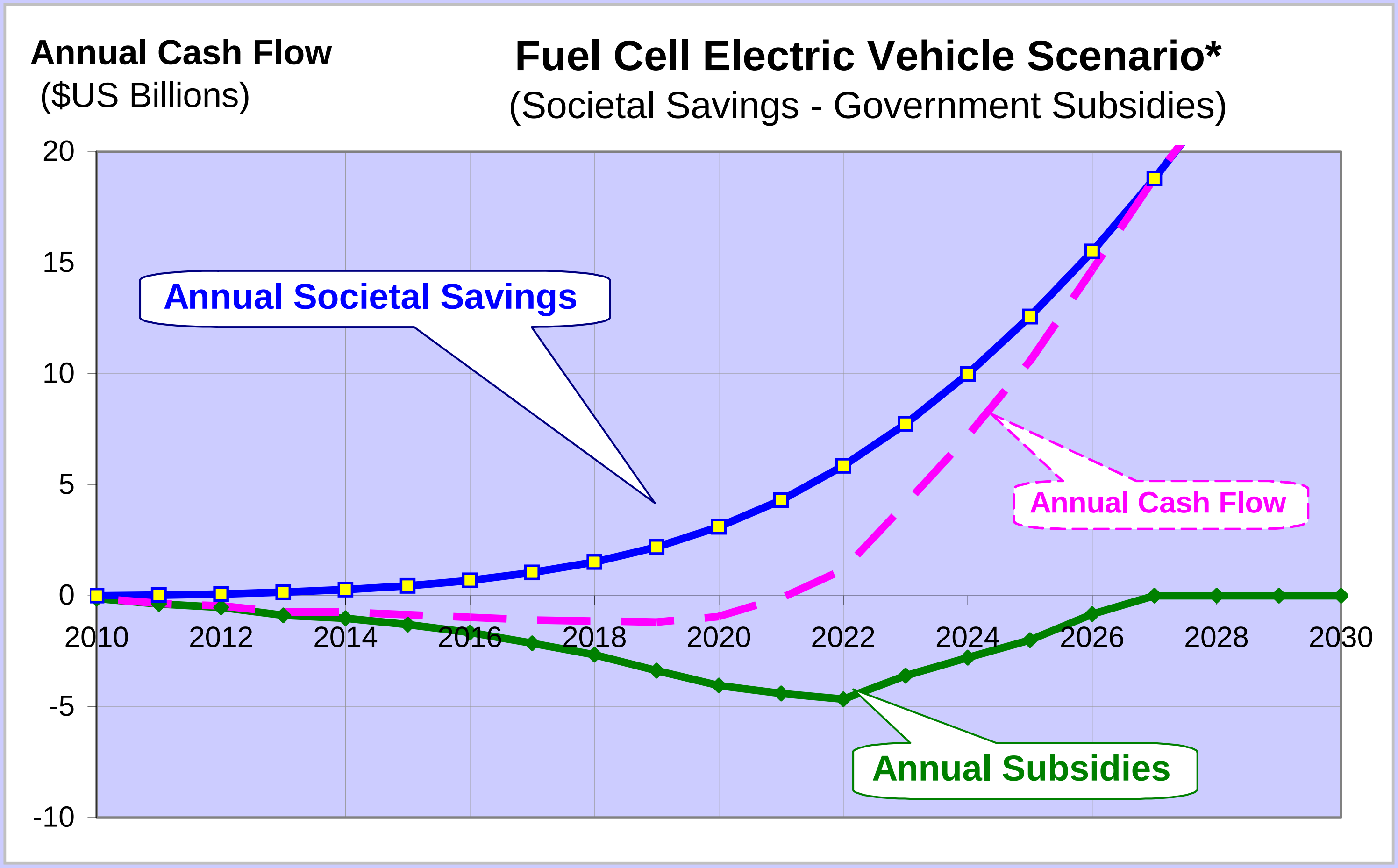
# Societal Cash Flow

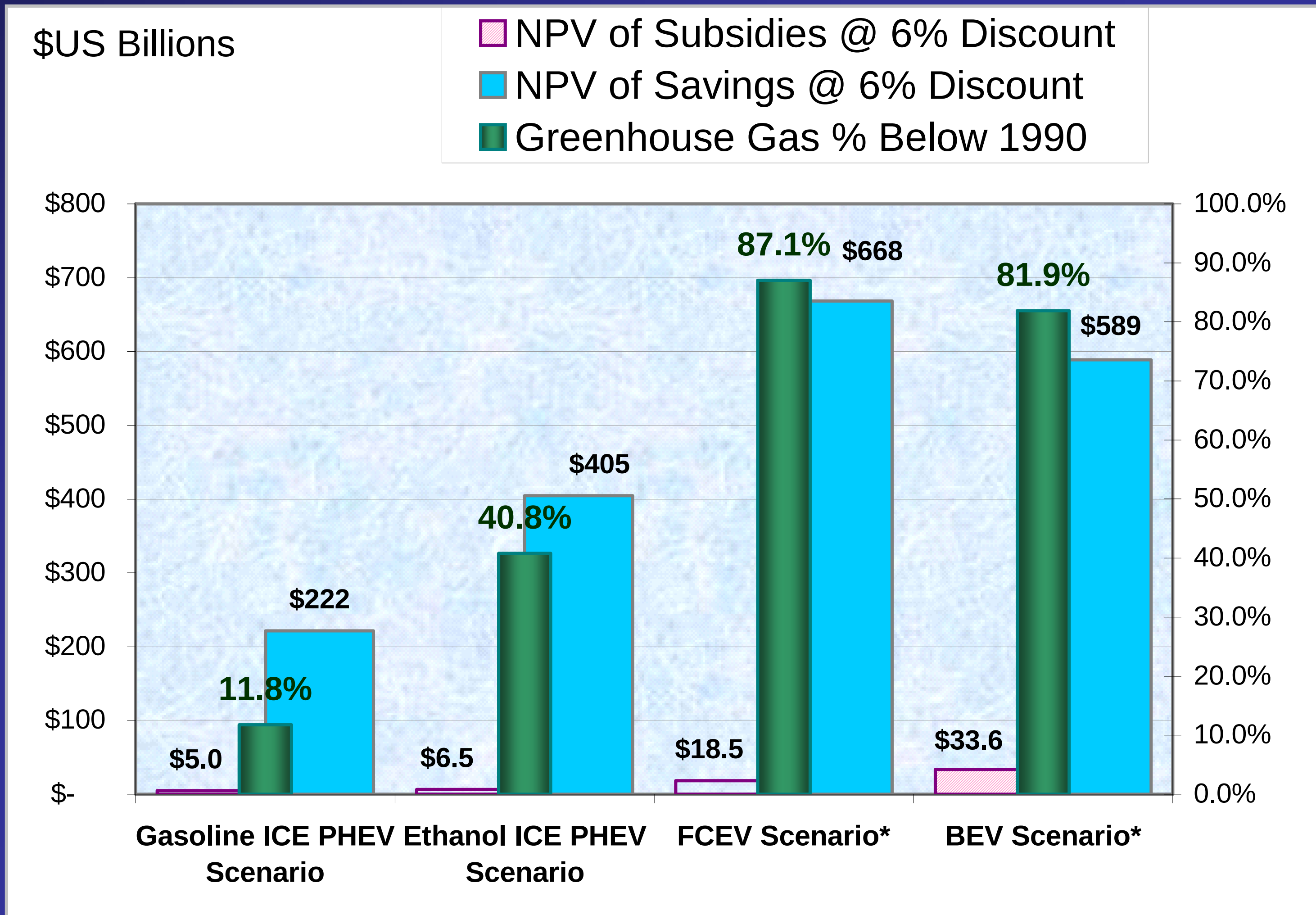



* Costs and savings include those for the PHEVs

Story Economics.XLS; Tab 'Graphs'; Z 32 5/15 /2009

| | | | | | |
|---|---|---|---|---|---|
| Total Subsidies | $ | 36.5 | Billion | | |
| Total Societal Savings | $ | 15,863 | Billion | Ratio NPV/ Subsidies: | 18.33 |
| Net Present Value | $ | 668.2 | Billion | (at 6% Discount) | |

# Net Present Value of Societal Costs & Benefits






Story Economics.XLS; Tab 'NPV'; K 49 5/15 /2009

* FCEV & BEV scenario incentives include those for ICE PHEVs in each scenario

# HGM 10000: Filling 100 cars or 15 busses/day


All-in life cycle costs today: Production: $3.26/kg*

Production, compression & storage: $4.83/kg

($2.04/gallon-range equivalent basis)

* Natural gas = $8.00/MBTU

# …and we have the capacity to meet growing demand.

# HGM-2000 Field Units



# Conclusions

- All-electric vehicles are required, in conjunction with ICE hybrids, plug-in ICE hybrids and biofuels, to *simultaneously*:
  - **Reduce GHG's to 80% below 1990 levels**
  - **Achieve petroleum energy "quasi-independence"**
  - **Nearly eliminate urban air pollution***
- Fuel cells have significant advantages over batteries for full-function, long-range all-electric vehicles.
- Government incentives are modest compared to the societal benefits and other past and present government projects

* With the exception of particulates from brake & tire wear

# Key References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2. Thomas, C.E, "Comparison of Transportation Options in a Carbon-Constrained World: Hydrogen, Plug-in Hybrids and Biofuels," Proceedings of the National Hydrogen Association Annual Meeting, Sacramento, California, March 31, 2008.
3. The National Hydrogen Association, "Energy Evolution: an analysis of alternative vehicles and fuels to 2100" http://www.hydrogenassociation.org/general/evolution.asp
4. Sinha, Jayanti, Stephen Lasher, Yong Yang and Peter Kopf, "Direct hydrogen PEMFC manufacturing cost estimation for automotive applications," Fuel Cell Tech Team Review, September 24, 2008, Tiax LLC.
5. Wang, Michael Q., "Greenhouse gases, Regulated Emissions, and Energy use in Transportation, the Argonne National Laboratory; Argonne has also released version 2.8a that includes the impact of vehicle manufacturing .http://www.transportation.anl.gov/software/GREET/
6. Dhameja S., *Electric Vehicle Battery Systems*, Newnes Press, Boston 2002
7. Wipke K, S.Sprik, J. Kurtz, and T. Ramsden, "Controlled hydrogen fleet and infrastructure demonstration and validation protect," National Renewable Energy Laboratory Report NREL/TR-560-45451, slide CDP#38, March 2009.
8. Morrow K, Karner D, Francfort J, "Plug-in hybrid electric vehicle charging infrastructure review," Final Report INL/EXT-08-15058, Idaho National Laboratory, November 2008
9. Kromer M, Heywood J, "Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet," Sloan Automotive Laboratory, Massachusetts Institute of Technology, Publication No. LFEE 2007-03 RP, May 2007.
10. Duvall, M., Khipping, E., "Environmental assessment of PHEVs, Vol 1 – National greenhouse gas emissions," Electric Power Research Institute/Natural Resources Defense Council Report # 1015325, July 2007

H2Gen

# Thank You

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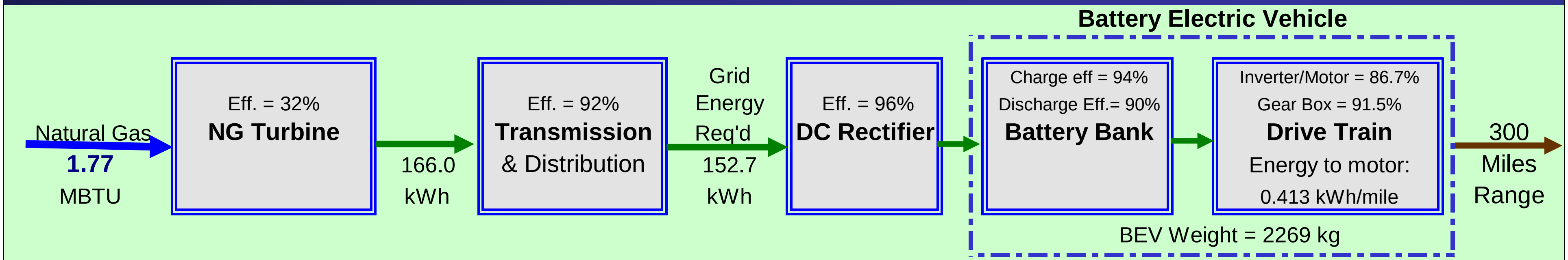
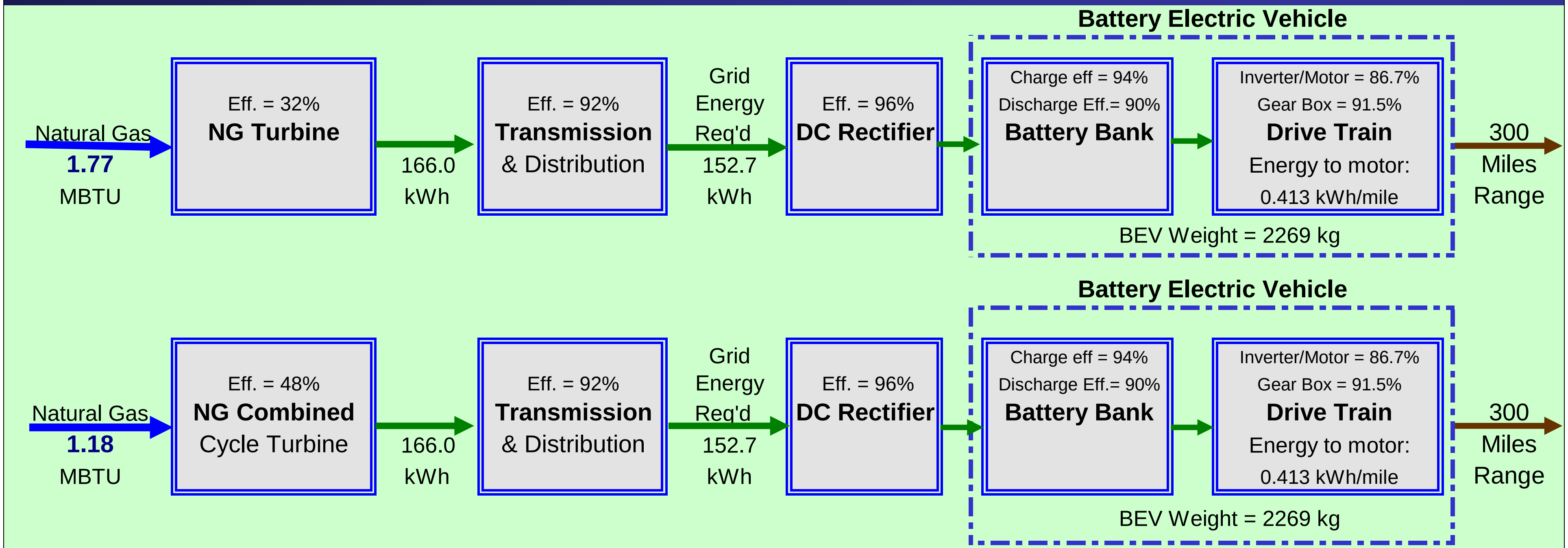
# Backup Slides

# Natural Gas: Battery EVs via Electricity? Or Fuel Cell EVs via Hydrogen?

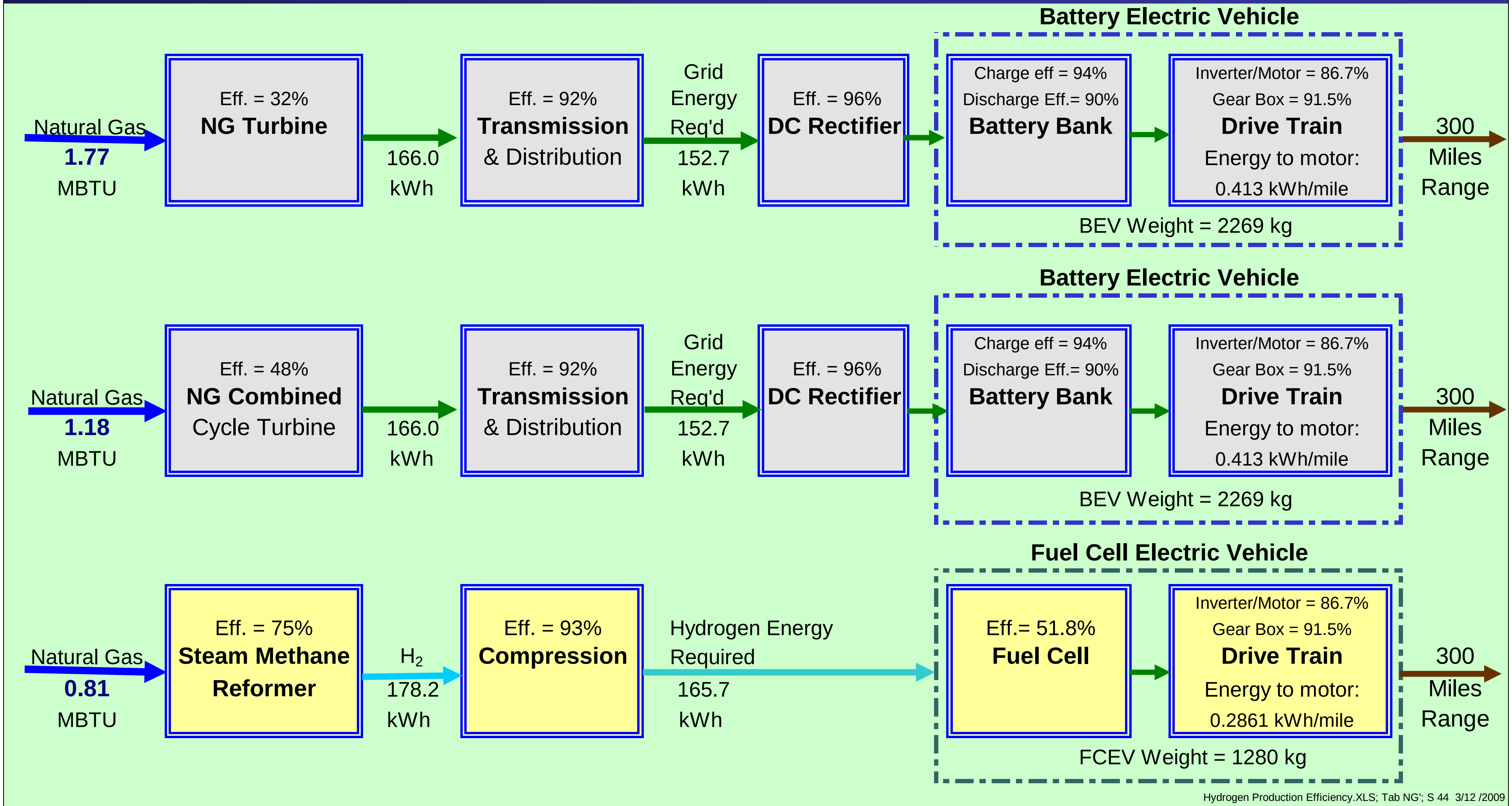
H2Gen



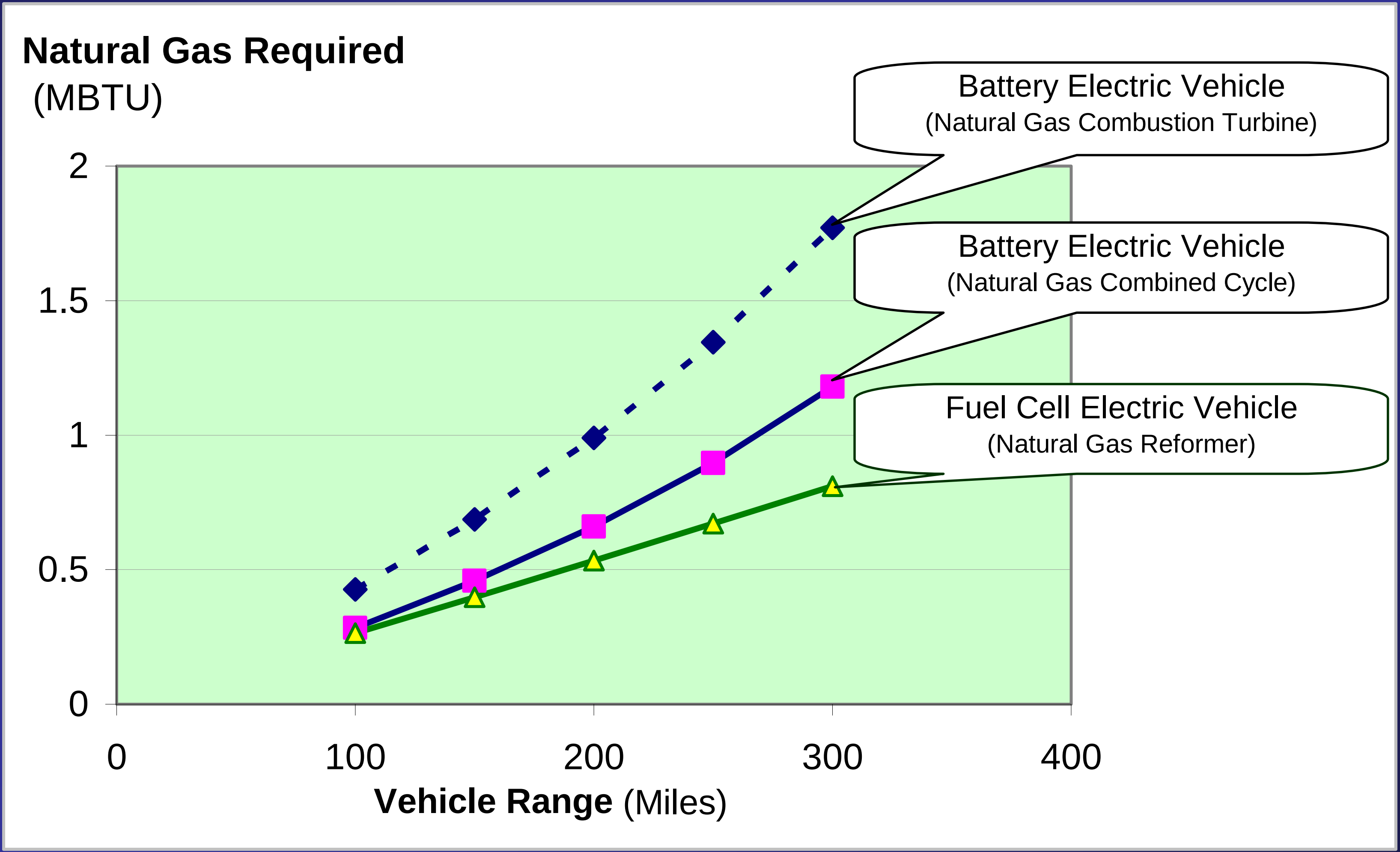
# Natural Gas: Battery EVs via Electricity? Or Fuel Cell EVs via Hydrogen?



# Natural Gas: Battery EVs via Electricity? Or Fuel Cell EVs via Hydrogen?



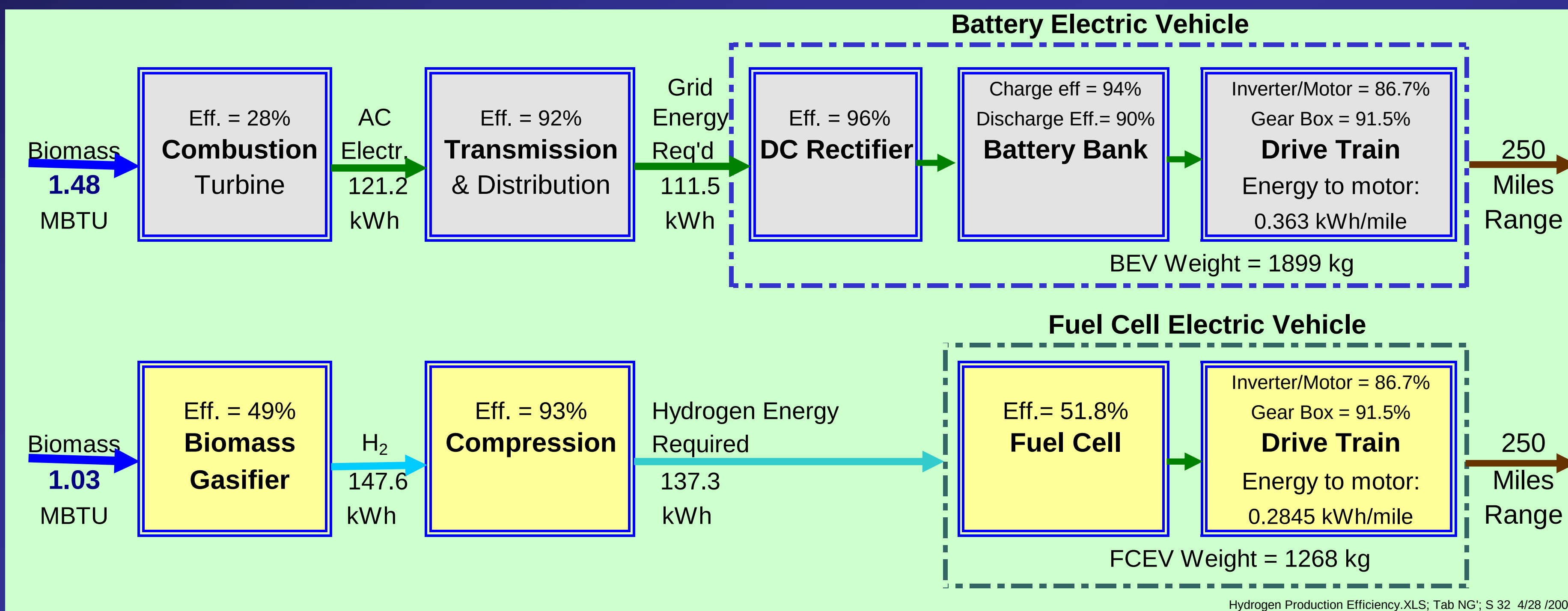
# Natural Gas Required for Electric Vehicles






Hydrogen Production Efficiency.XLS; Tab NG per mile'; AM 32 3/12 /2009

# Biomass Utilization:
# BEV or FCEV?

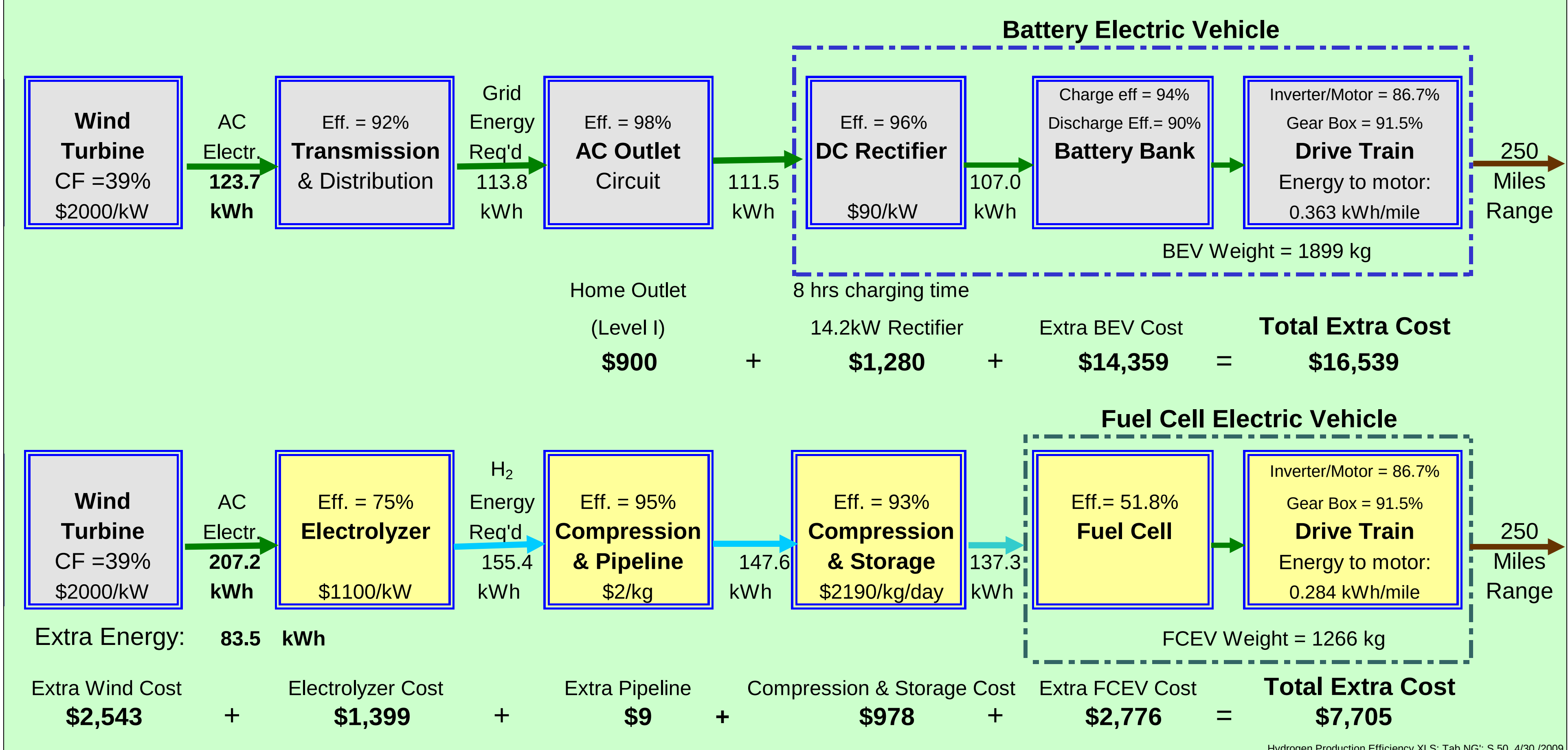



Biomass to electricity reference: Duvall, M., Khipping, E., "Environmental assessment of PHEVs Vol 1 – National greenhouse gas emissions," EPRI/NRDC Rept # 1015325, July 2007

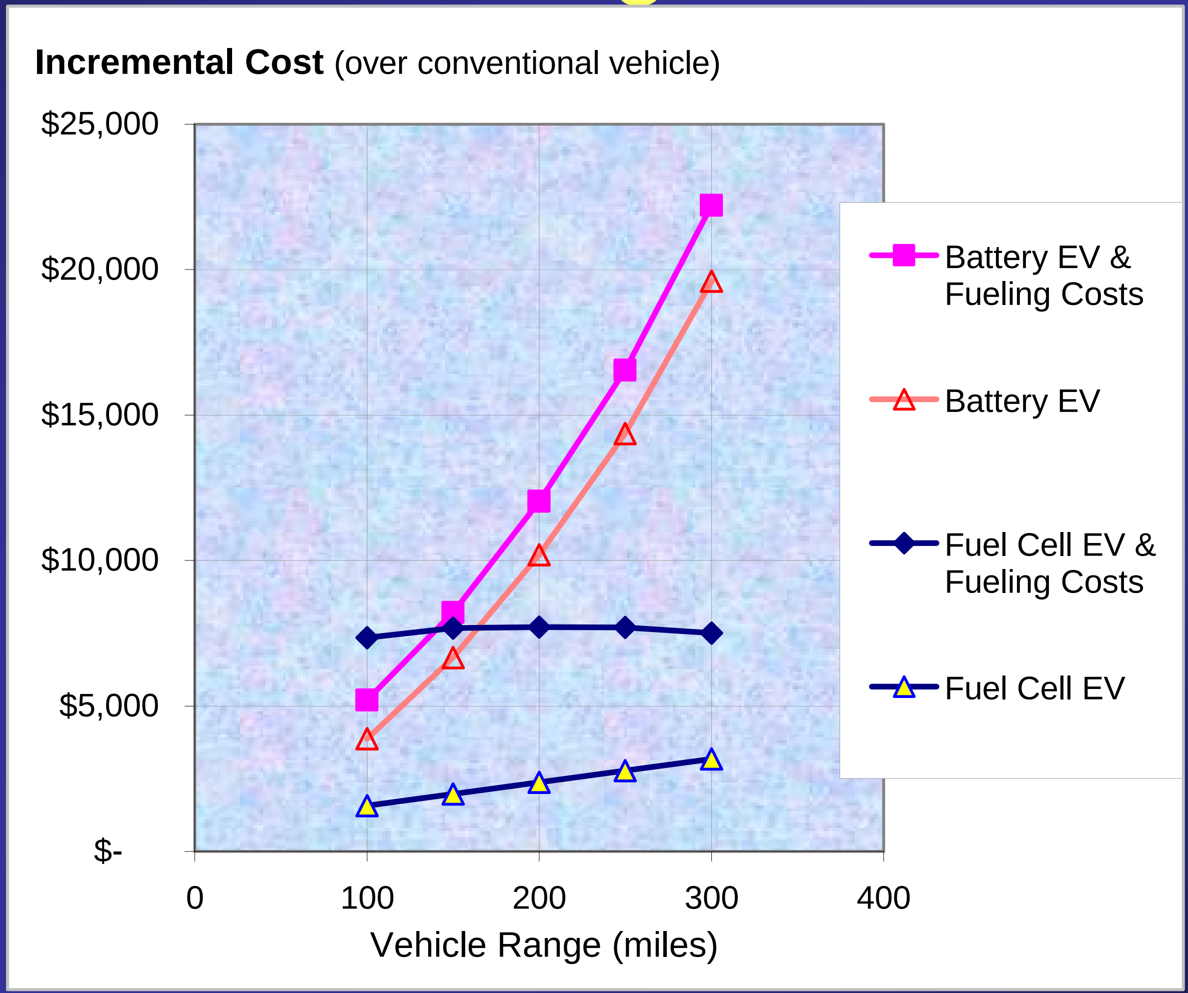
Biomass to hydrogen: Spath, P, Aden A, Eggeman T, Ringer M, Wallace B, Jechura J, "Biomass to hydrogen production detailed design and economics," NREL/TP-510-37408, May 2005

Vehicle parameters: 2.13 m^2 area, 0.33 drag, 0.0092 rolling resistance & 0 to 60 mph acceleration in 10 seconds

# Wind Electricity: BEV or FCEV?



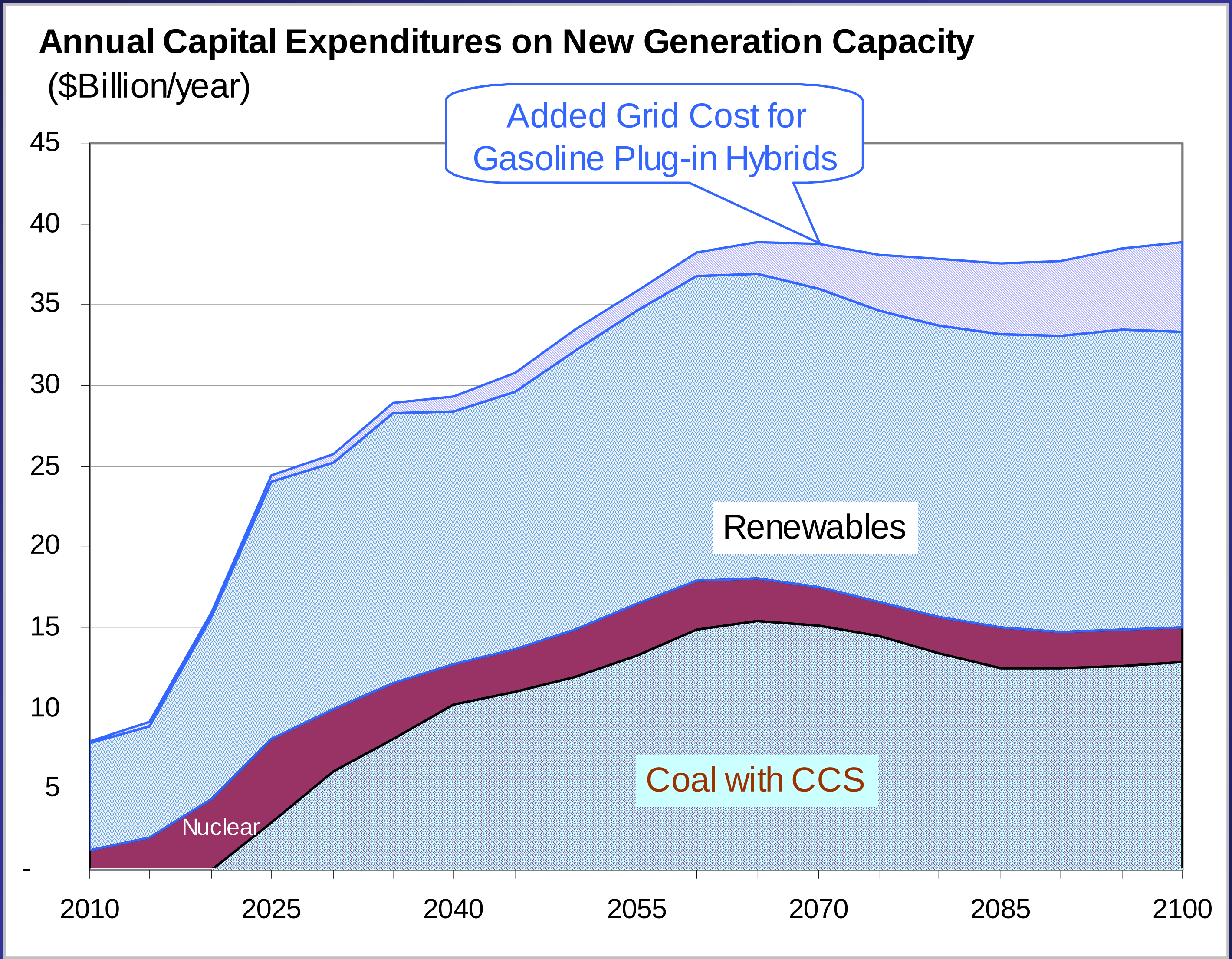
# Incremental Cost: Vehicle + Fueling Costs






Hydrogen Production Efficiency.XLS; Tab NG per mile'; AM 41 4/30 /2009

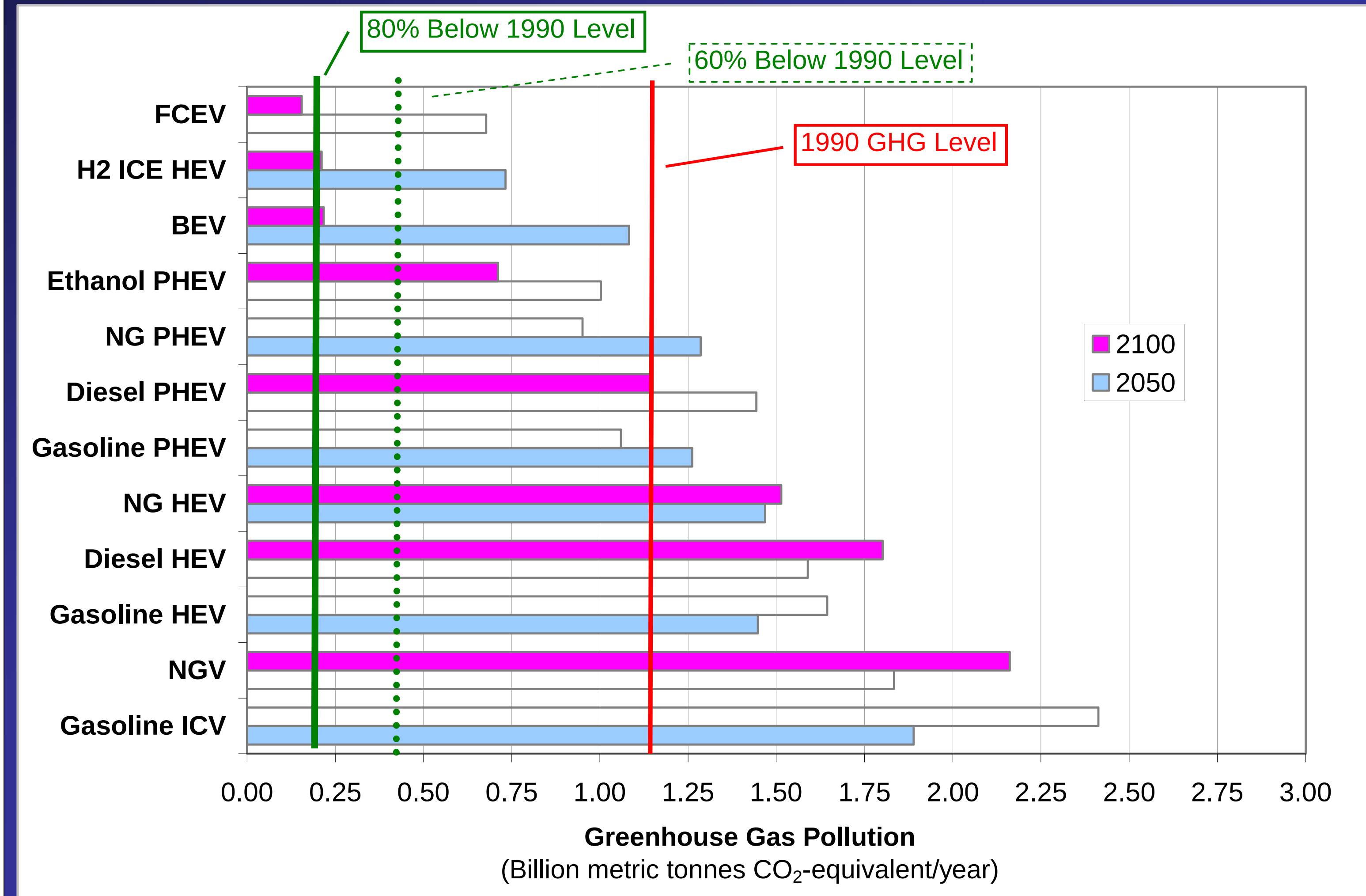
# Cost to Reduce Grid Carbon Footprint




Source: EPRI for generator capital costs and capacity factors

# Greenhouse Gas Pollution Comparisons (2050 & 2100)

H2Gen




GHG = greenhouse gases

FCEV = fuel cell hybrid electric vehicle

HEV = hybrid electric vehicle

PHEV = plug-in hybrid electric vehicle

NG = natural gas

NGV = natural gas vehicle

ICV = internal combustion engine vehicle

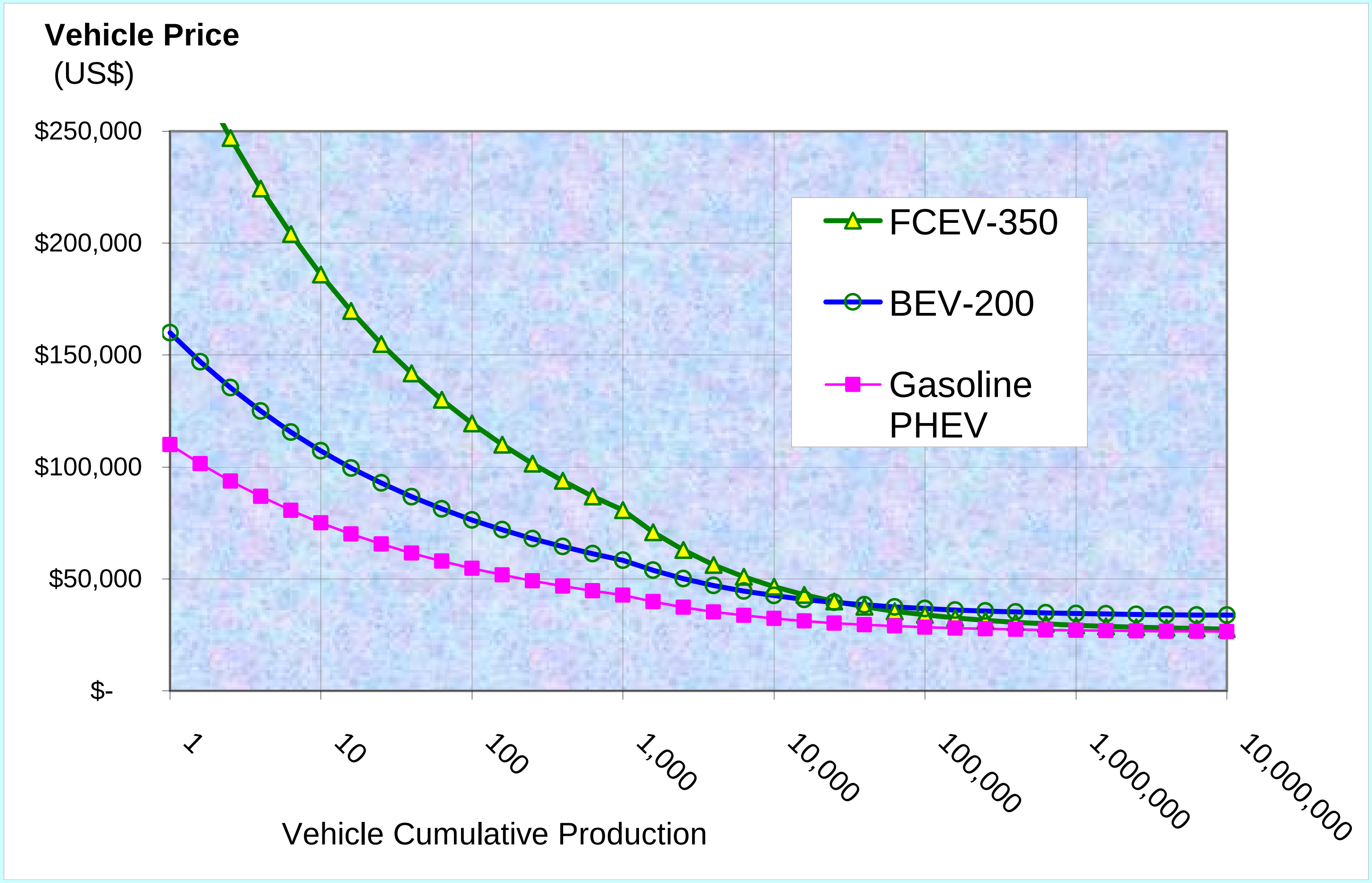


Story Simultaneous.XLS; Tab 'Graphs'; BJ 464 5/15 /2009

Based on AEO 2009 data

# Vehicle Costs vs. Production Volume

H2Gen




| | Initial Cost | Final Cost | Incremental Cost (2030) |
|---|---|---|---|
| FCEV-350 | $ 300,000 | $ 26,600 | $ 3,600 |
| BEV -200 | $ 160,000 | $ 33,300 | $ 10,300 |
| PHEV | $ 110,000 | $ 26,162 | $ 3,709 |

Story Simultaneous.XLS; Tab 'Progress Ratios'; AF 49 5 /15 /2009

# DOE FY2010 Budget Request

H2Gen

| ($1,000's) | FY 2008 Appropriation | FY 2009 Current Appropriation | FY 2009 Additional Appropriation | FY 2010 Request | Decrease ('10-'09) |
|---|---|---|---|---|---|
| Fuel Cell Technologies | | | | | |
| Fuel Cell Systems R&D | 54,201 | 75,700 | | 63,213 | **(12,487)** |
| Hydrogen Production and Delivery R&D | 38,607 | 10,000 | | **0** | **(10,000)** |
| Hydrogen Storage R&D | 42,371 | 59,200 | | **0** | **(59,200)** |
| *Fuel Cell Stack Component R&D* | - | - | - | **0** | **-** |
| Technology Validation* | 29,612 | ***15,000*** | | **0** | **(15,000)** |
| Transportation Fuel Cell Systems | 6,218 | 6,600 | | **0** | **(6,600)** |
| Distributed Energy Fuel Cell Systems | - | - | 13,400 | **0** | **-** |
| Fuel Processor R&D | - | - | - | **0** | **-** |
| Safety Codes and Standards* | 15,442 | ***12,500*** | - | **0** | **(12,500)** |
| Education* | 3,865 | ***4,200*** | - | **0** | **(4,200)** |
| Systems Analysis | 11,099 | 7,713 | | 5,000 | **(2,713)** |
| Market Transformation | - | 4,747 | 30,000 | **0** | **(4,747)** |
| Manufacturing R&D | 4,826 | 5,000 | | **0** | **(5,000)** |
| Actual Total Fuel Cell Technologies | 206,241 | 200,660 | 43,400 | 68,213 | **(132,447)** |
| Total Fuel Cell Technologies reported in request: | 206,241 | 168,960 | 43,400 | 68,213 | **(100,747)** |
| Funding buried in footnotes for FY'09 (pg 62) | | 31,700 | | | |

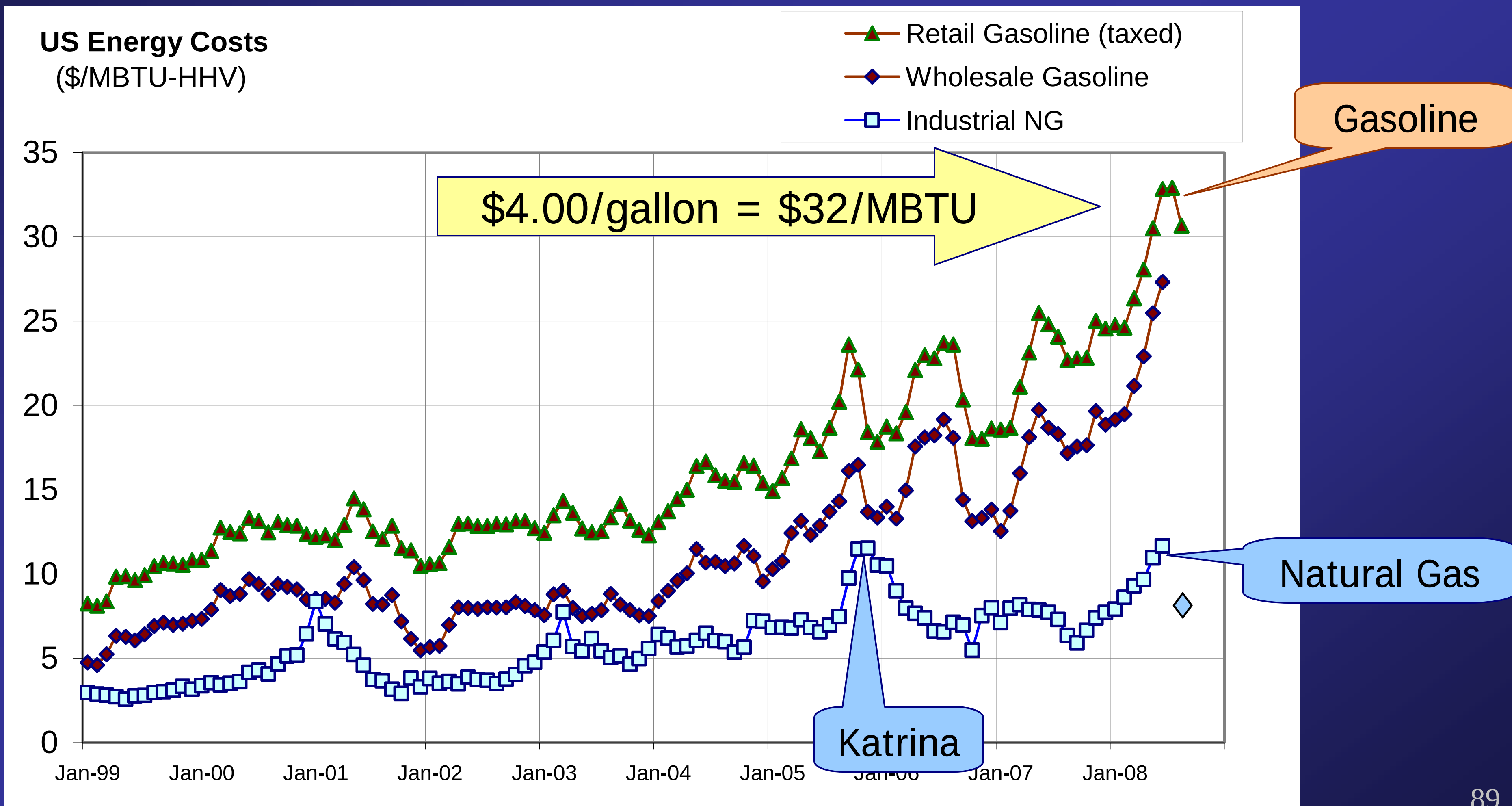
*These items were included in "Vehicle Technologies" for FY 2009 only
(They were transferred back to FC Technologies for FY2010 at zero levels!)

(dollars in thousands)

| | FY 2008 Current Appropriation[a] | FY 2009 Original Appropriation | FY 2009 Additional Appropriation | FY 2010 Request |
|---|---|---|---|---|
| Energy Efficiency and Renewable Energy | | | | |
| Fuel Cell Technologies | 206,241 | 168,960 | 43,400 | 68,213 |
| Biomass and Biorefinery Systems R&D | 195,633 | 217,000 | 786,500[b] | 235,000 |
| Solar Energy | 166,320 | 175,000 | – | 320,000 |
| Wind Energy | 49,034 | 55,000 | 118,000 | 75,000 |
| Geothermal Technology | 19,307 | 44,000 | 400,000 | 50,000 |
| Water Power | 9,654 | 40,000 | – | 30,000 |
| Vehicle Technologies | 208,359 | 273,238 | – | 333,302 |
| Building Technologies | 107,382 | 140,000 | – | 237,698 |
| Industrial Technologies | 63,192 | 90,000 | 50,000 | 100,000 |
| Federal Energy Management Program | 19,818 | 22,000 | – | 32,272 |
| RE-ENERGYSE | – | – | – | 115,000 |
| Facilities and Infrastructure | 76,176 | 76,000 | 100,700[b] | 63,000 |
| Weatherization and Intergovernmental Activities | 282,217 | 516,000[c] | 11,600,000 | 301,000 |
| Program Direction | 104,057 | 127,620 | 50,000 | 238,117 |
| Program Support | 10,801 | 18,157 | – | 120,000 |
| Congressionally Directed | 186,664 | 228,803 | – | 0 |
| Advanced Battery Manufacturing | – | – | 2,000,000 | – |
| Transportation Electrification | – | – | 400,000 | – |
| Alternative Fueled Vehicles | – | – | 300,000 | – |
| EERE RDD&D | – | – | 951,400 | – |
| Subtotal, Energy Efficiency and Renewable Energy | 1,704,855 | 2,191,778 | 16,800,000 | 2,318,602 |

[a] SBIR/STTR funding was transferred to the Science Appropriation in FY 2008, which includes a reduction of $16,355,000 that was transferred to the SBIR program, and $1,960,000 that was transferred to the STTR program.
[b] Facilities and Infrastructure includes $13.5 million for the Integrated Biorefinery Research Facility, for a total of $800 million in Biomass related Recovery funded projects.
[c] Includes $250.0 million in emergency funding for the Weatherization Assistance Grants program provided by P.L. 111-6, "The Continuing Appropriations Resolution, 2009."

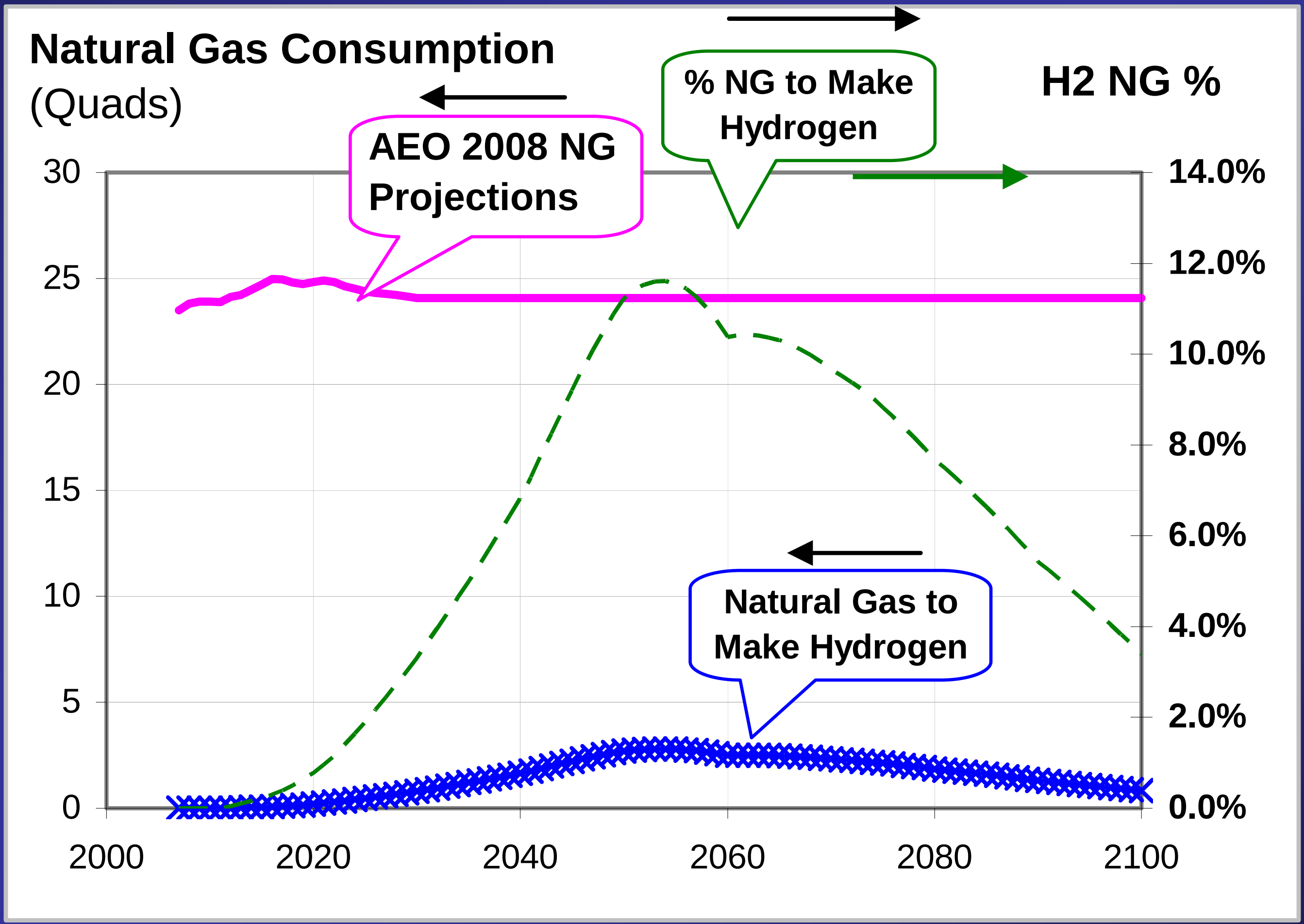
# Natural Gas vs. Gasoline Prices





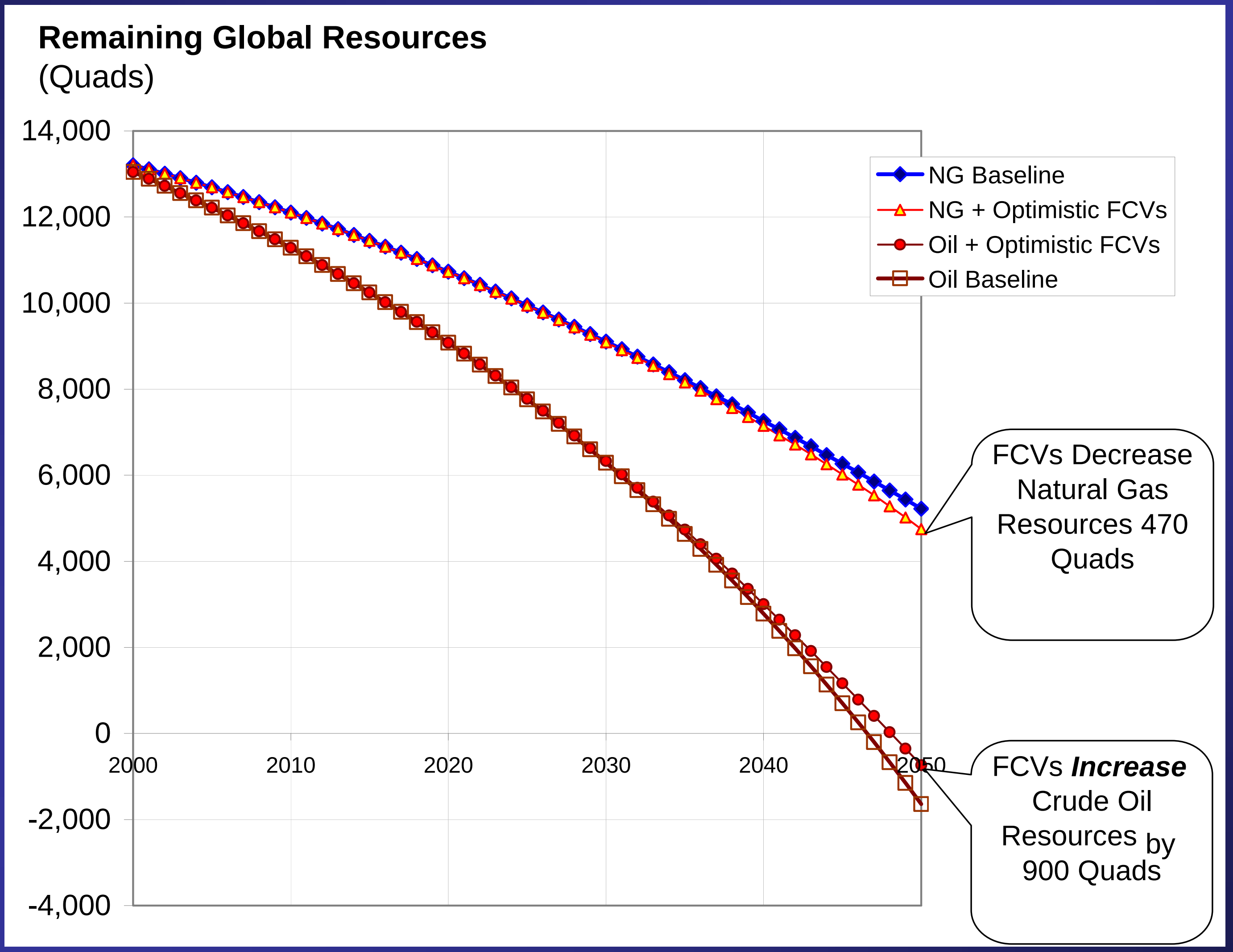

H2Gen: NG-Price.XLS; Tab 'Gasoline-NG' T100- 9 / 13 / 2008

# Natural Gas use for FCVs




H2 Energy Story.XLS; Tab 'NG 2008'; U 76 3/21 /2008

# Impact of FCVs on Global Natural Gas Resources




H2 Energy Story.XLS; Tab 'NG-Oil Resources';BA141 - 2 / 28 / 2008

# Marginal Grid Mix Illustration

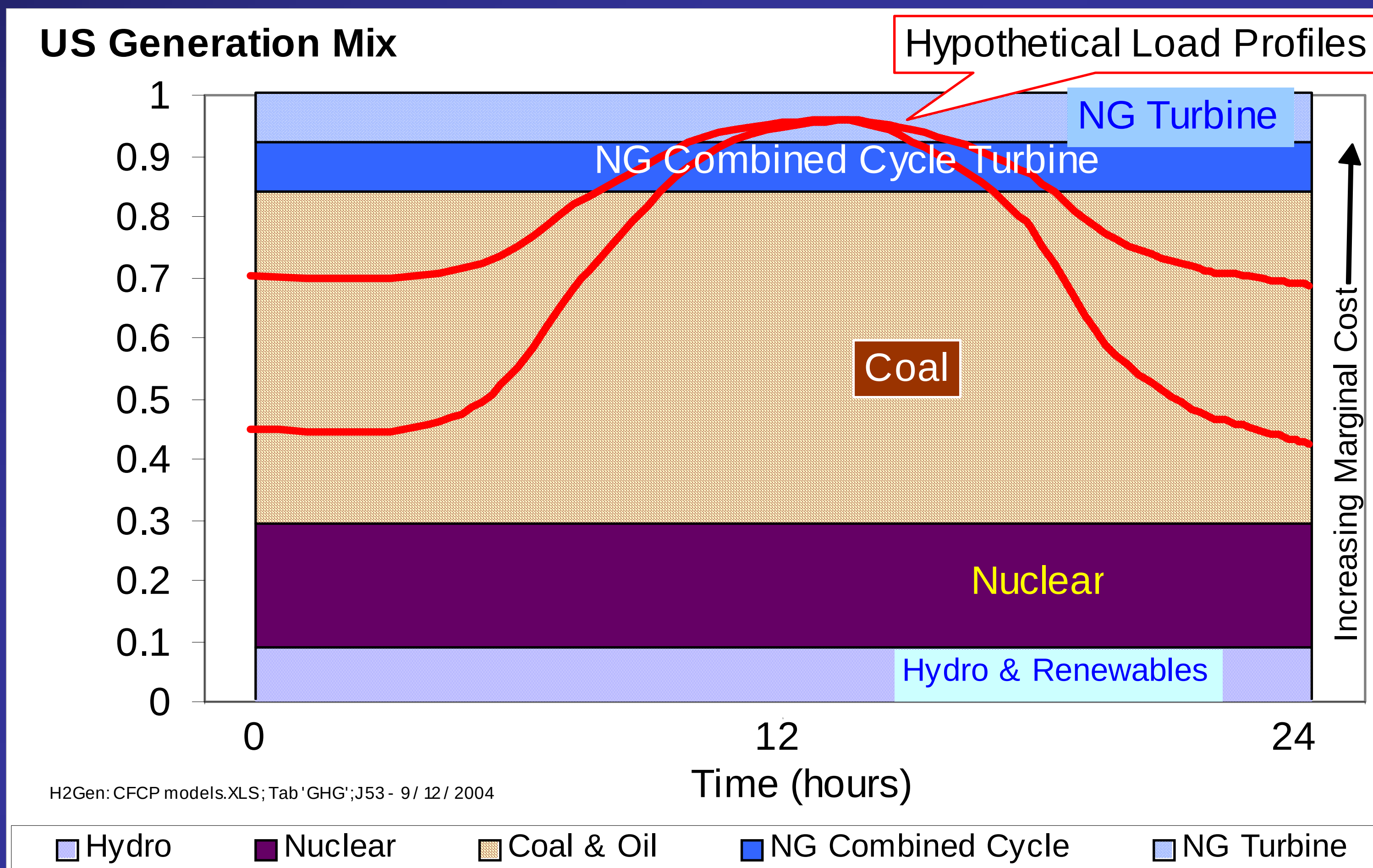





**Figure . Illustration of marginal grid loads for a typical US electric utility**

# Societal Cost / Benefit Results

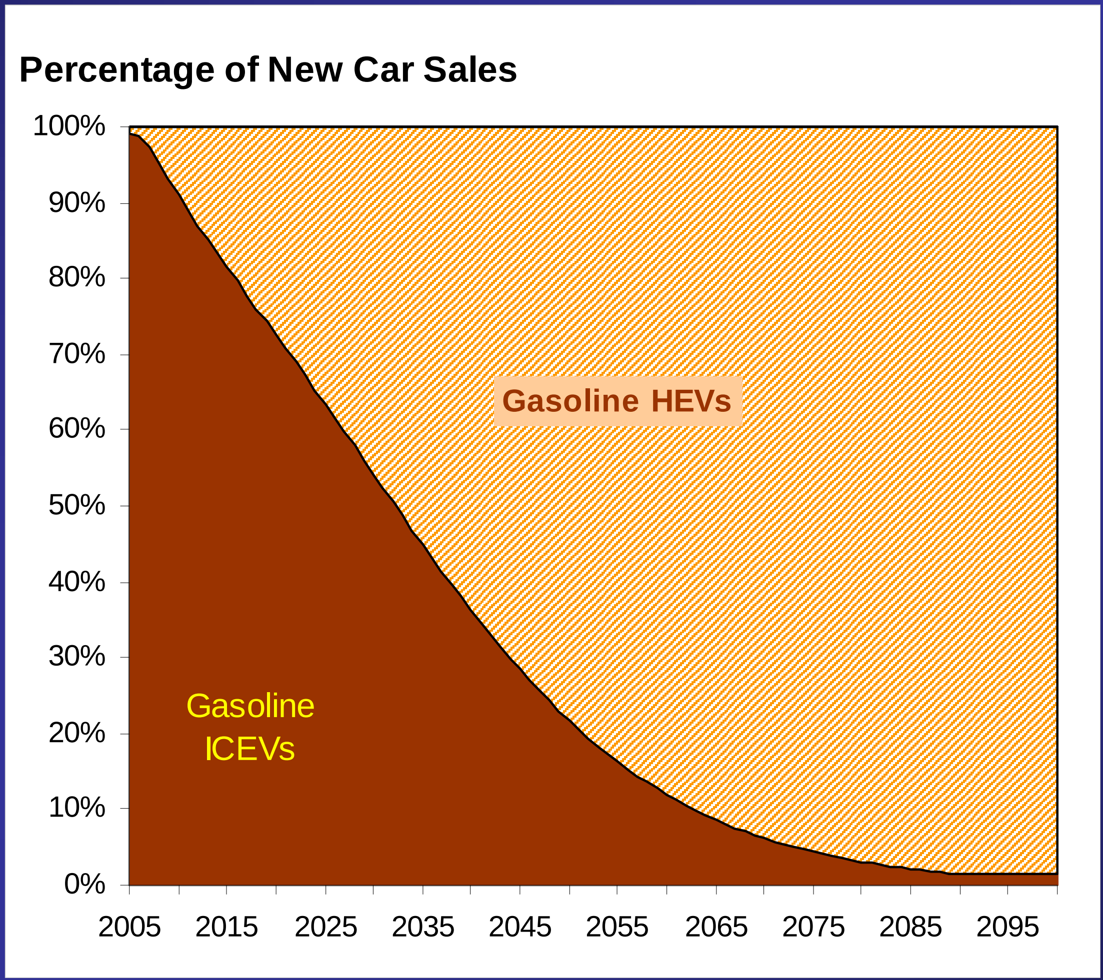
| | Gasoline ICE PHEV Scenario | Ethanol ICE PHEV Scenario | FCEV Scenario* | BEV Scenario* |
|---|---|---|---|---|
| Total Subsidies & Investments ($US Billions) | $ 8.6 | $ 12.4 | $ 36.5 | $ 79.2 |
| Total Societal Savings ($US Billions) | $ 5,635 | $ 9,565 | $ 15,863 | $ 15,293 |
| Ratio of Savings / Subsidies | 653 | 769 | 435 | 193 |
| | | | | |
| Discount Rate = 6% | | | | |
| NPV of Subsidies & Investments ($ Billions) | $ 5.0 | $ 6.5 | $18.47 | $ 33.6 |
| NPV of Societal Savings ($US Billions) | $ 221.6 | $ 404.7 | $ 668.2 | $ 588.5 |
| Ratio of NPV(Savings) / NPV (Subsidies) | 44.3 | 62.6 | 36.2 | 17.5 |
| **Greenhouse Gas % Below 1990 Levels** | **11.8%** | **40.8%** | **87.1%** | **81.9%** |

*Note: FCEV & BEV Scenarios include incentives for gasoline & ethanol PHEVs in those scenarios

Story Economics.XLS; Tab 'NPV'; K 18 5/15 /2009

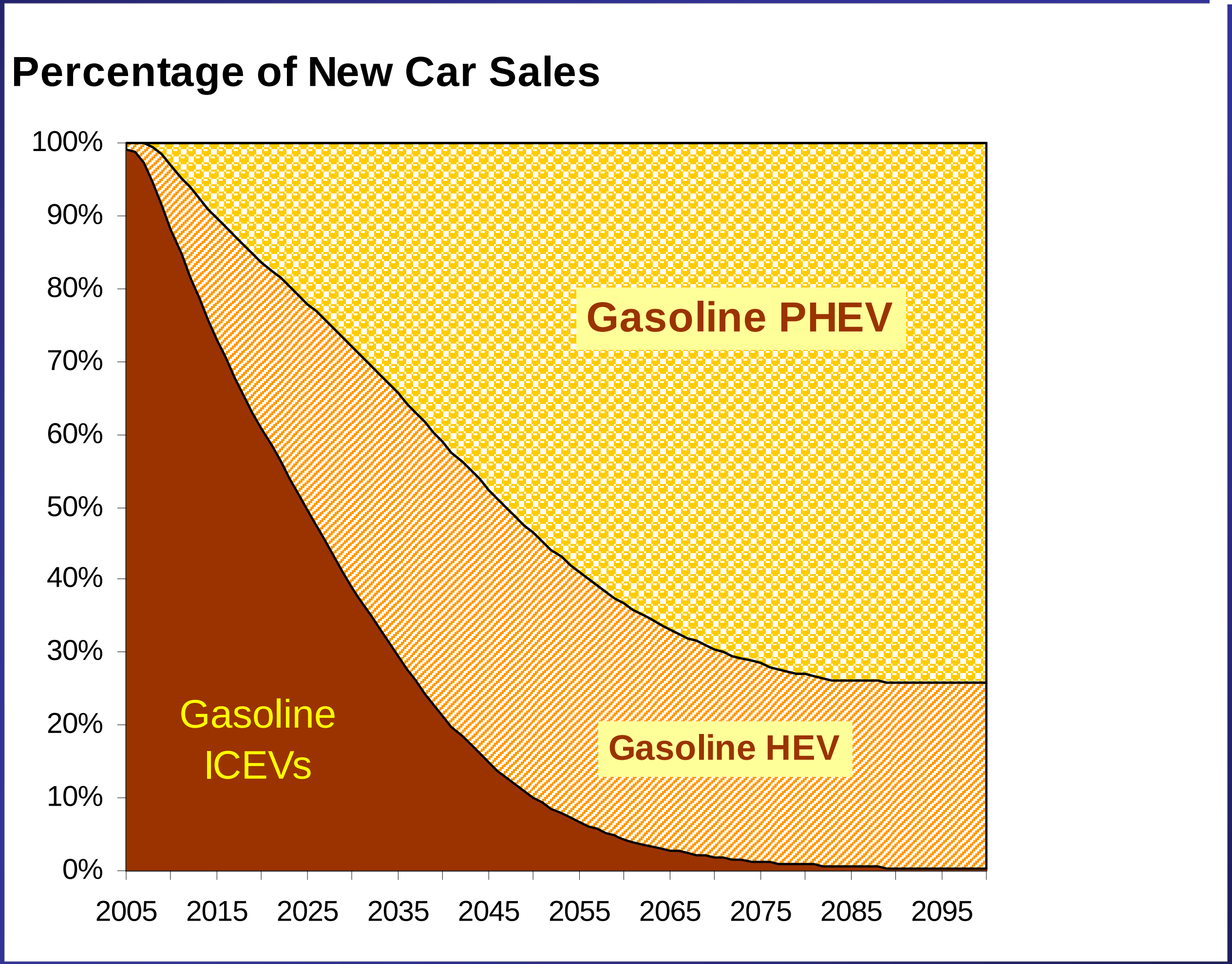
* FCEV & BEV scenario incentives include those for ICE PHEVs in each scenario

# Gasoline ICE Hybrid Scenario Market Shares




(50% Market Share Potential by 2024)

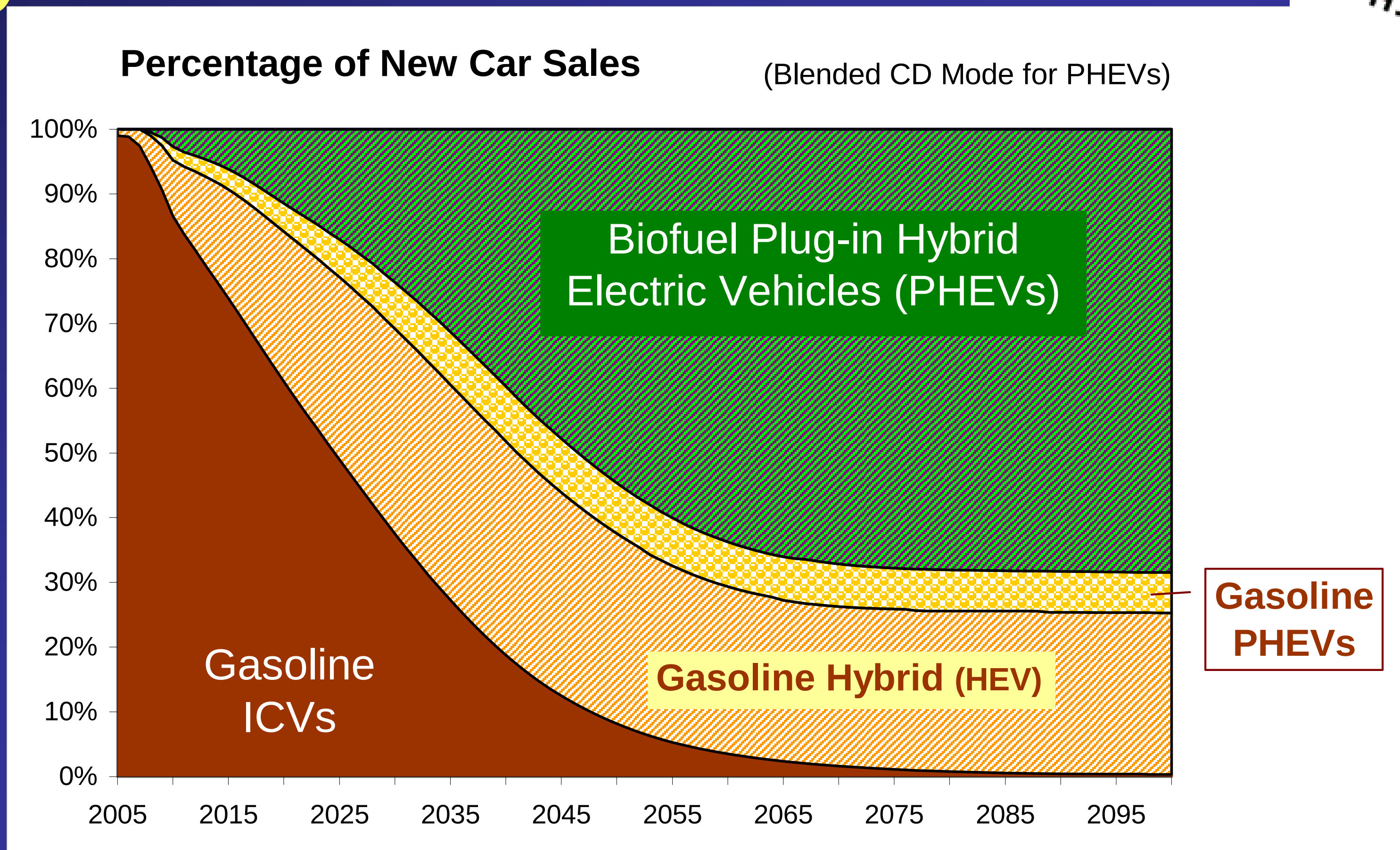
# Gasoline (& Diesel) ICE Plug-In Hybrid Scenario Market Shares






(50% market share potential by 2031; 75% plug-in potential limited by charging outlet availability; 12 to 52 mile all-electric range; 18% to 65% of VMT from grid)

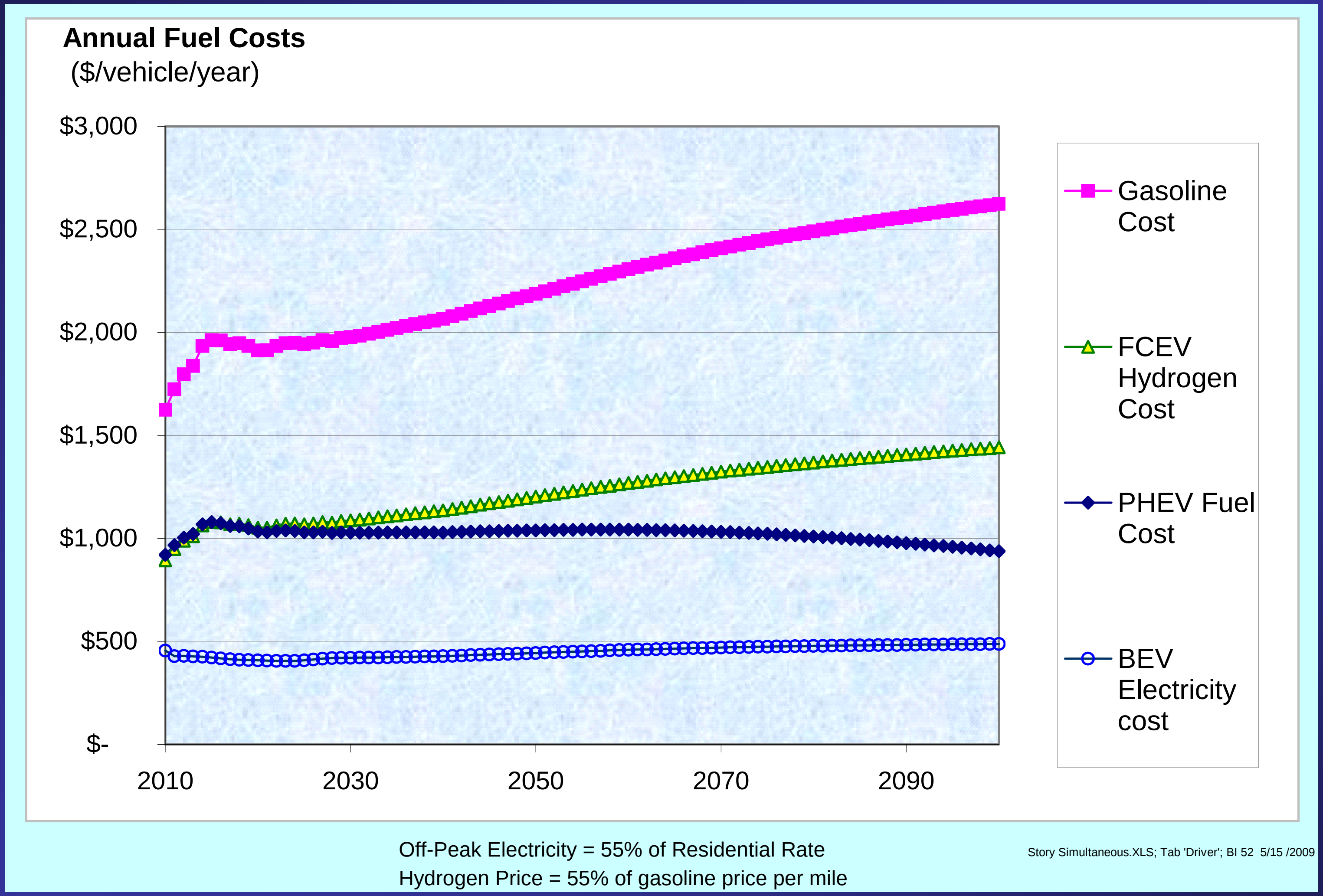
# Biofuel (eg. Ethanol) Plug-In Hybrid Scenario Market Shares




Story Simultaneous.XLS; Tab 'Graphs'; ED 30 3/4 /2009

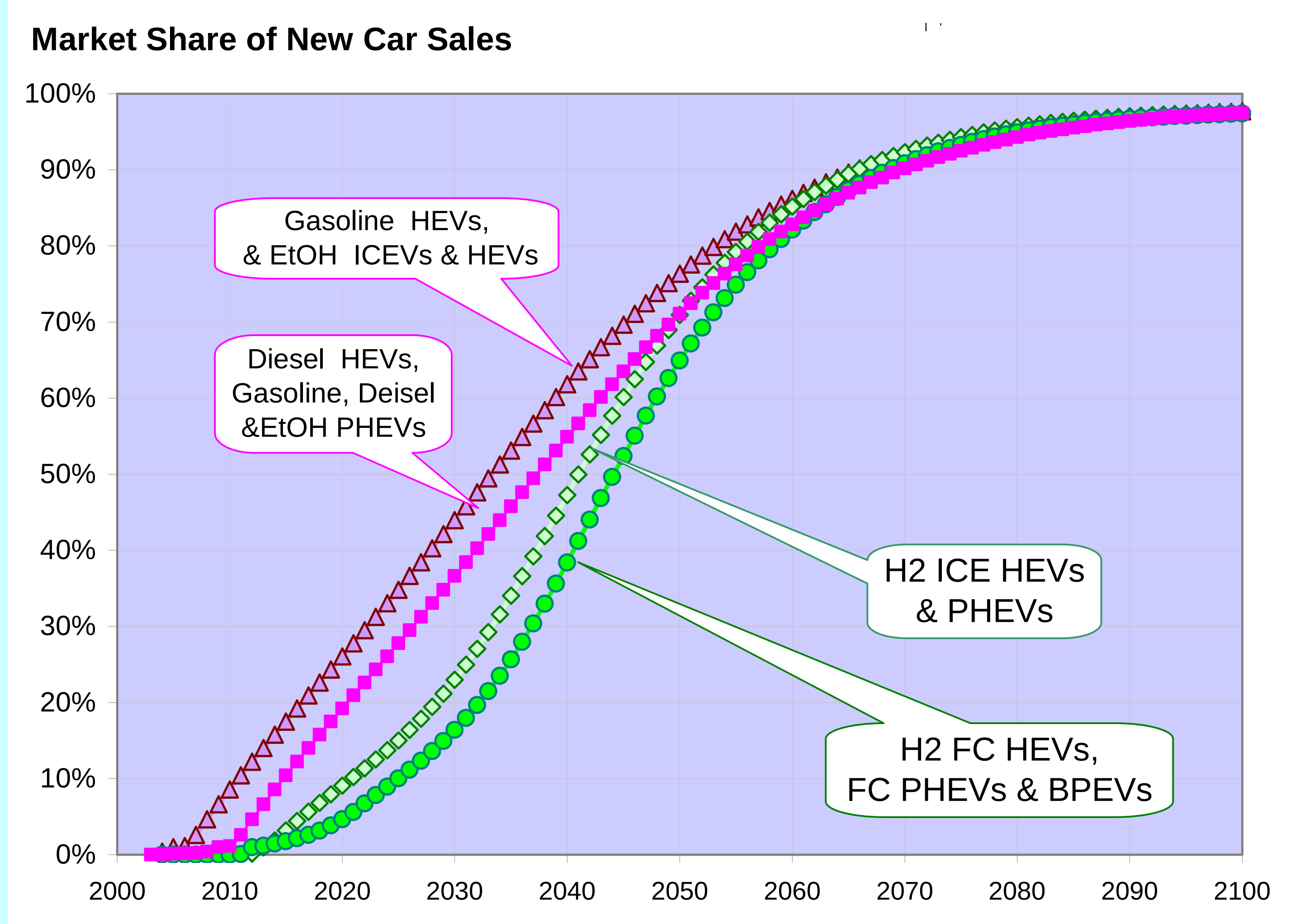
(50% market share potential by 2031; 75% plug-in potential limited by charging outlet availability; 12 to 52 mile all-electric range; 18% to 65% of VMT from grid; 90 billion gallon/year cellulosic ethanol production per Sandia/Livermore (vs. 9 B/yr now and 60 B gallons/yr limit used by NRC)

# Annual Fuel Costs ($/car/year)




[ Based on EIA Annual Energy Outlook 2009 through 2030 for gasoline price, natural gas price, residential electricity price, and vehicle miles traveled, with linear extrapolation to 2100; hydrogen price set at 55% the price of gasoline per mile traveled; off-peak electricity set at 55% of residential electricity price]

# Alternative Vehicle Market Penetration Assumptions




H2 Energy Story.XLS; Tab 'Annual Sales';IK 182 3/11 /2008

# Sensitivity Studies

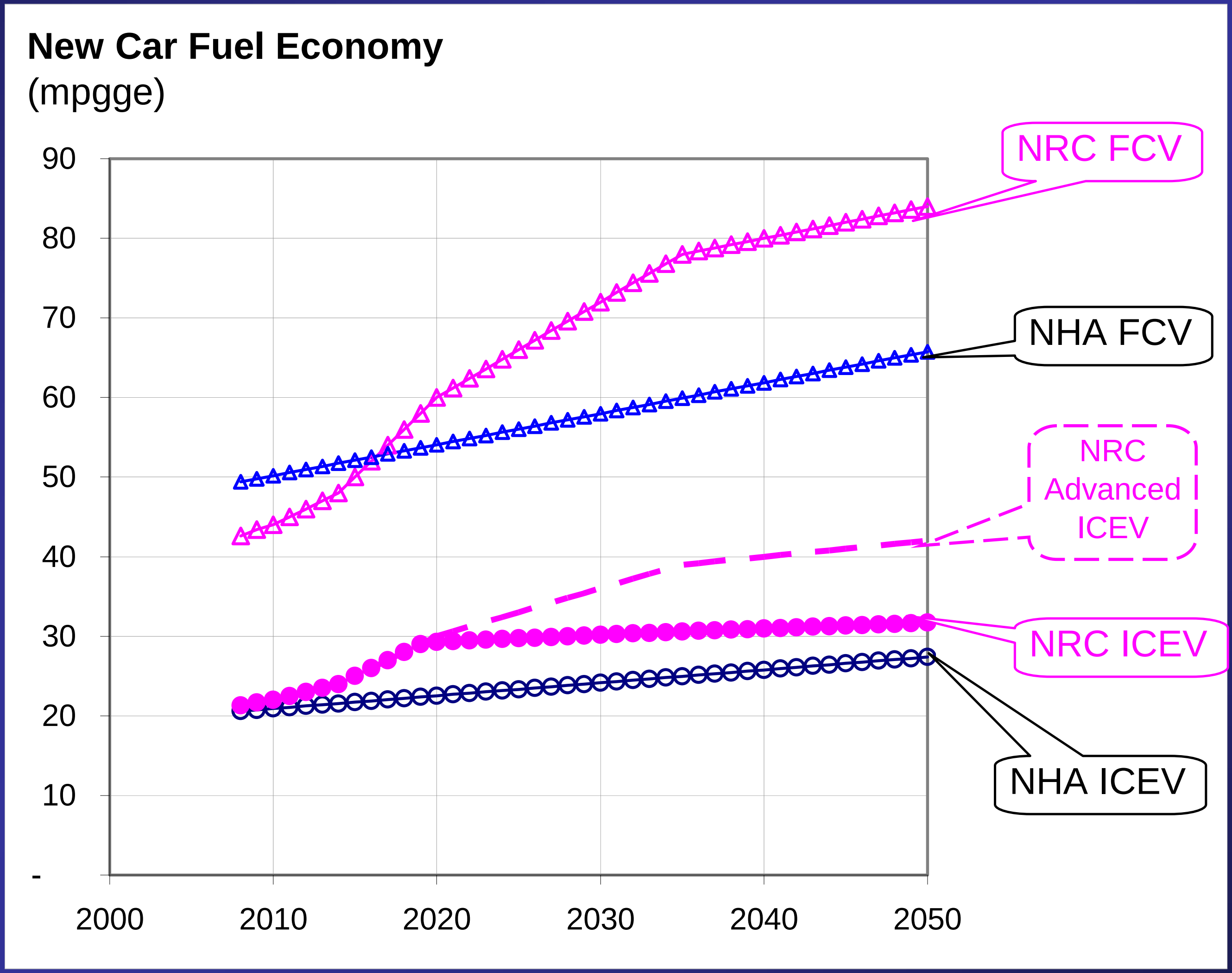
- NRC comparisons

# 2008 National Research Council Report vs. NHA Report

H2Gen

| | NRC Assessment | NHA Assessment |
|---|---|---|
| Alternative Vehicles Compared: | | |
| Gasoline ICEVs | Yes | Yes |
| Advanced ICEVs | Yes | Not separately |
| Gasoline HEVs | Yes | Yes |
| Gasoline PHEVs | NO | Yes |
| Ethanol HEVs | Yes ? | Yes |
| Ethanol PHEVs | NO | Yes |
| Diesel HEVs | NO | Yes |
| Diesel PHEVs | NO | Yes |
| NGVs | NO | Yes |
| NG HEVs | NO | Yes |
| NG PHEVs | NO | Yes |
| H2 ICE HEVs | NO | Yes |
| H2 ICE PHEVs | NO | Yes |
| H2 FCV HEVs | Yes ? | Yes |
| BEVs | NO | Yes |
| Societal Attributes Compared: | | |
| Oil Consumption | Yes | Yes |
| Greenhouse Gases | Yes | Yes |
| Urban Air Pollution | NO | Yes |
| Total Societal Cost | NO | Yes |
| | | |
| Time Horizon | To 2050 | To 2100 |
| Cellulosic Ethanol Production | 45 to 60 billion gallons/year | 120 billion gallons/year |

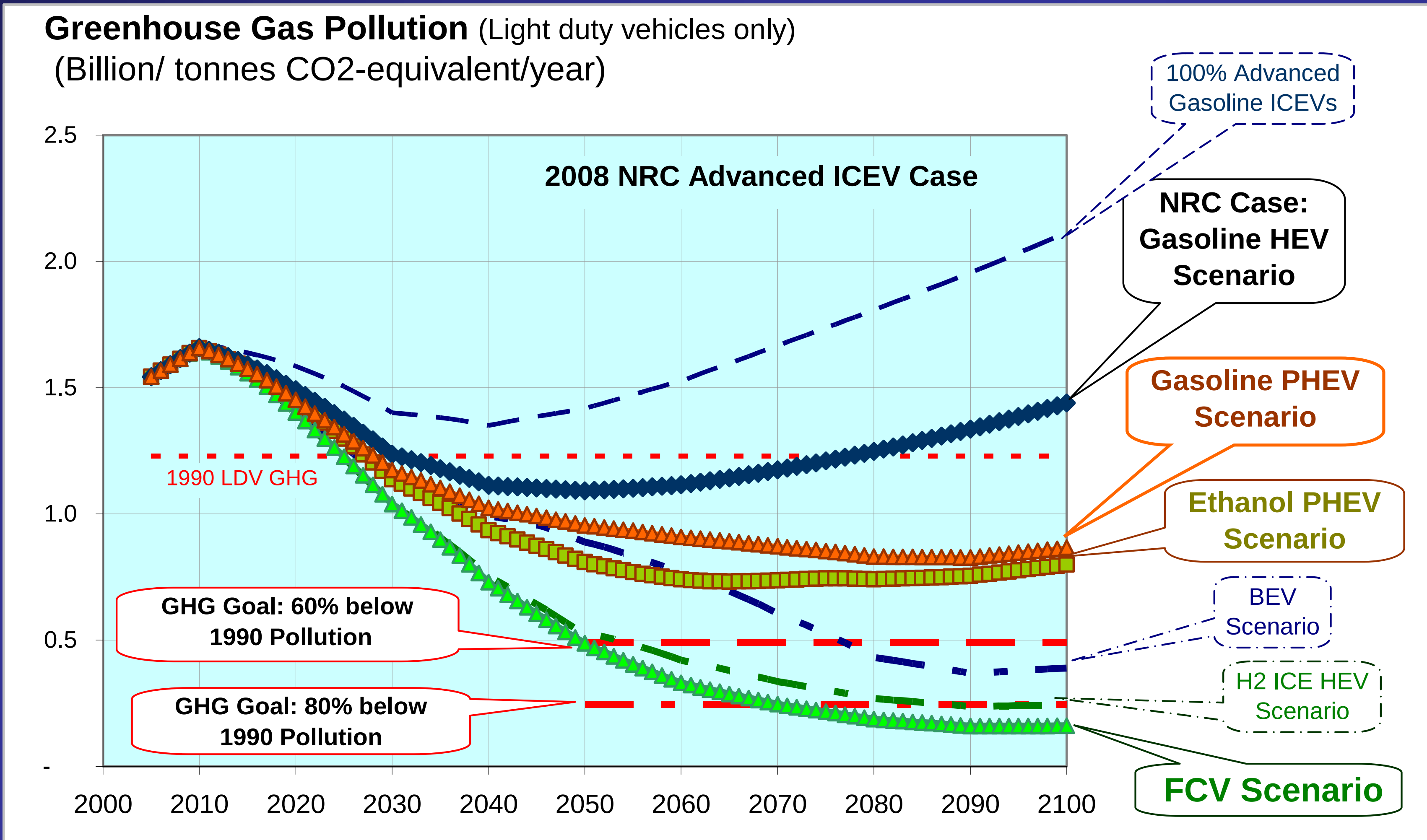
# Fuel Economy (NRC vs. NHA)






H2 Energy Story.XLS; Tab 'Fuel Economy';AF 74 2/16 /2009

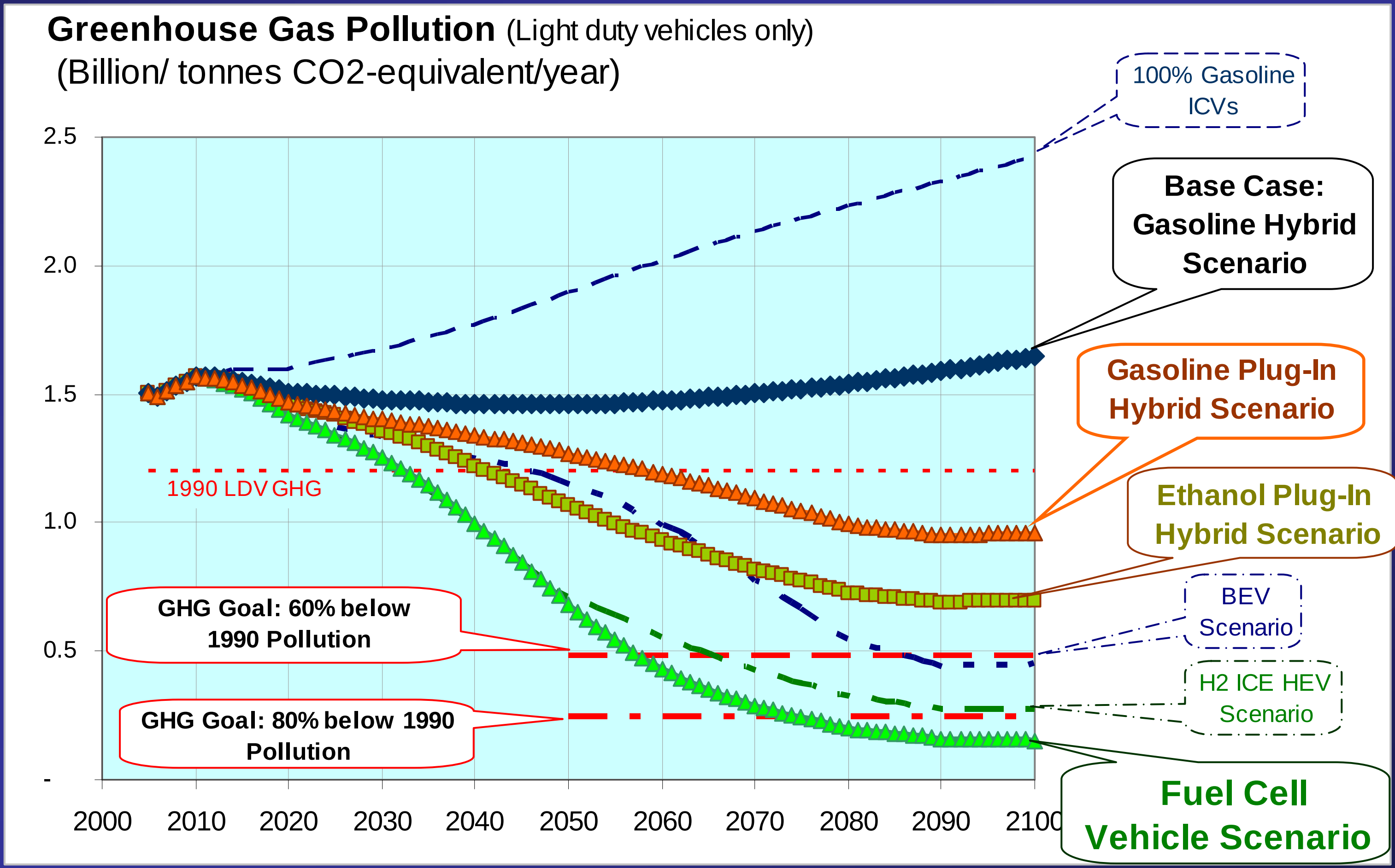
# GHG: NHA Model with NRC Input Data





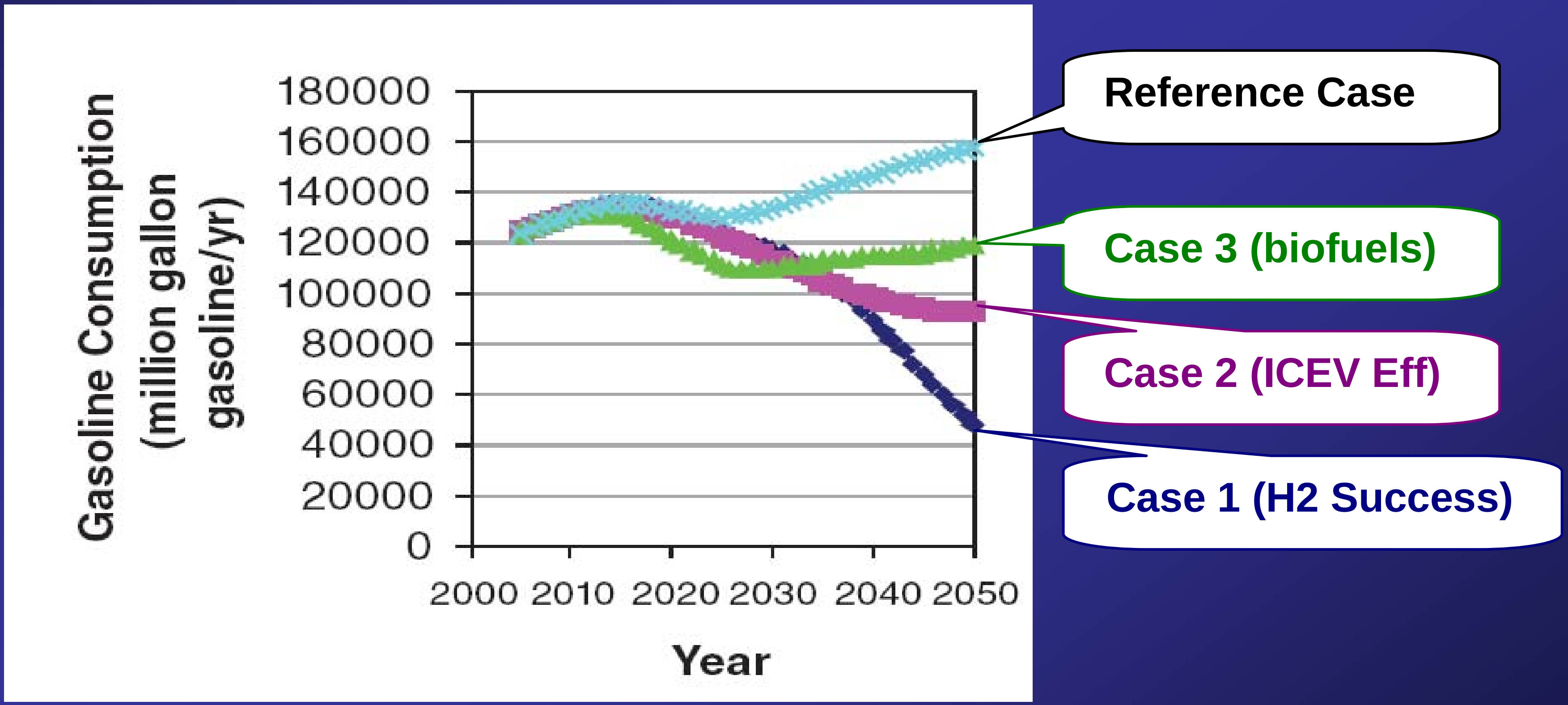

Story Simultaneous.XLS; Tab 'NRC Tables'; AJ 157 8/19 /2008

# GHG: NHA Model with NHA Input Data

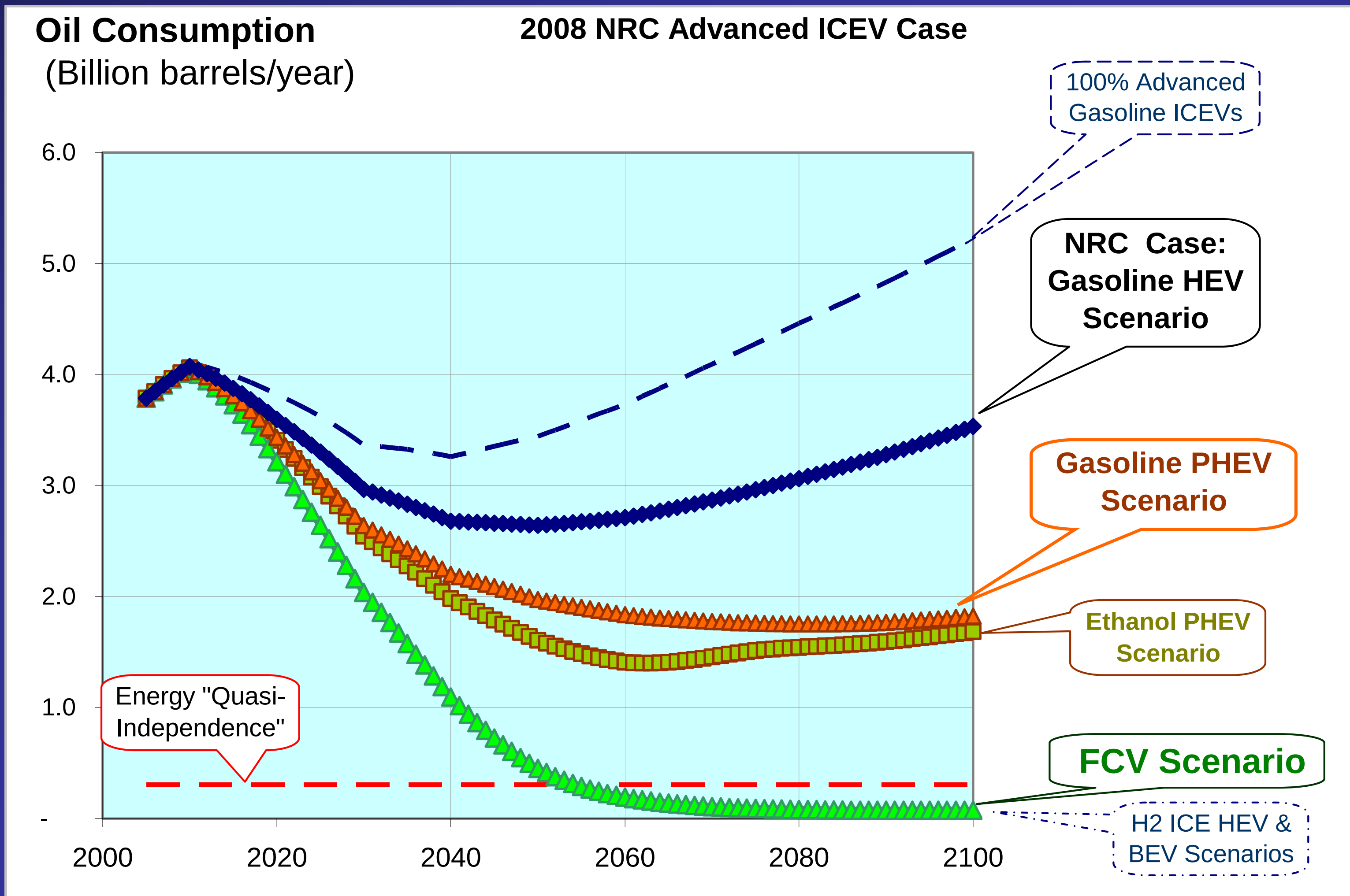


H2Gen

# NRC 2008 GHG Results



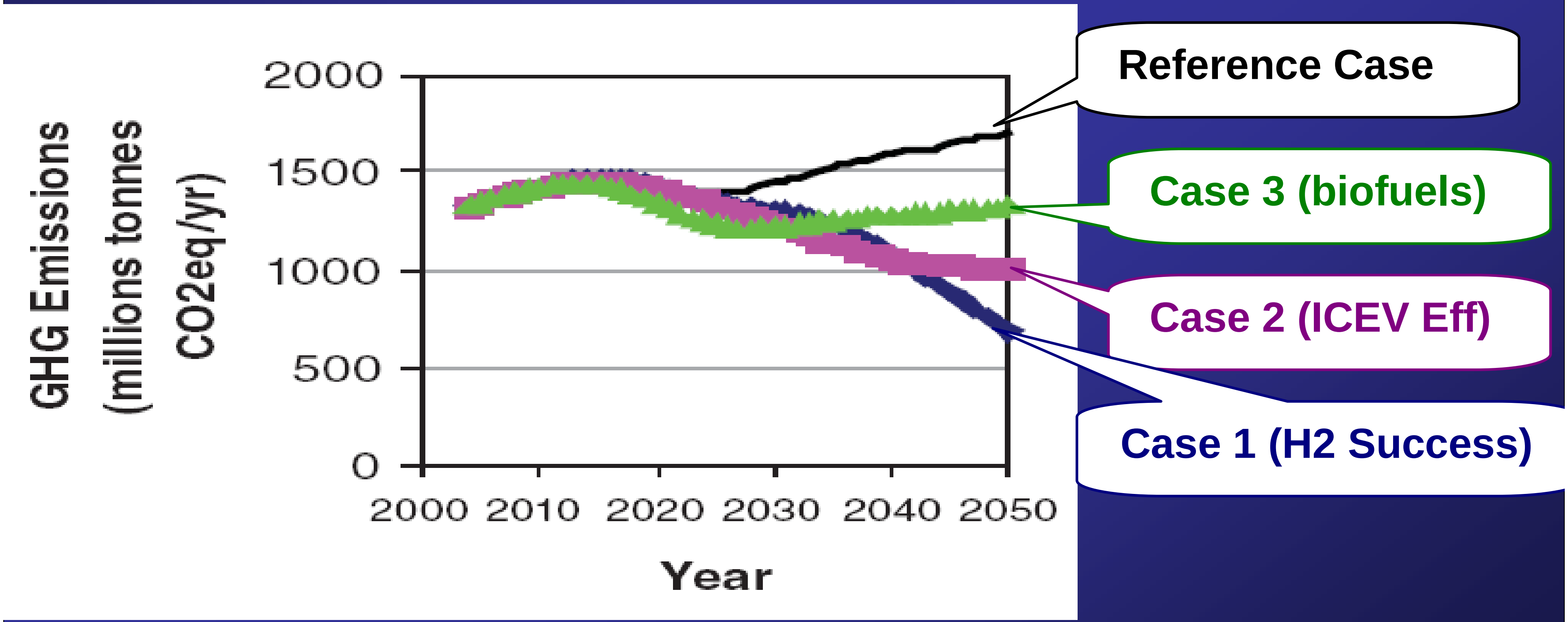
# Oil Consumption: NHA Model with NRC Input Data





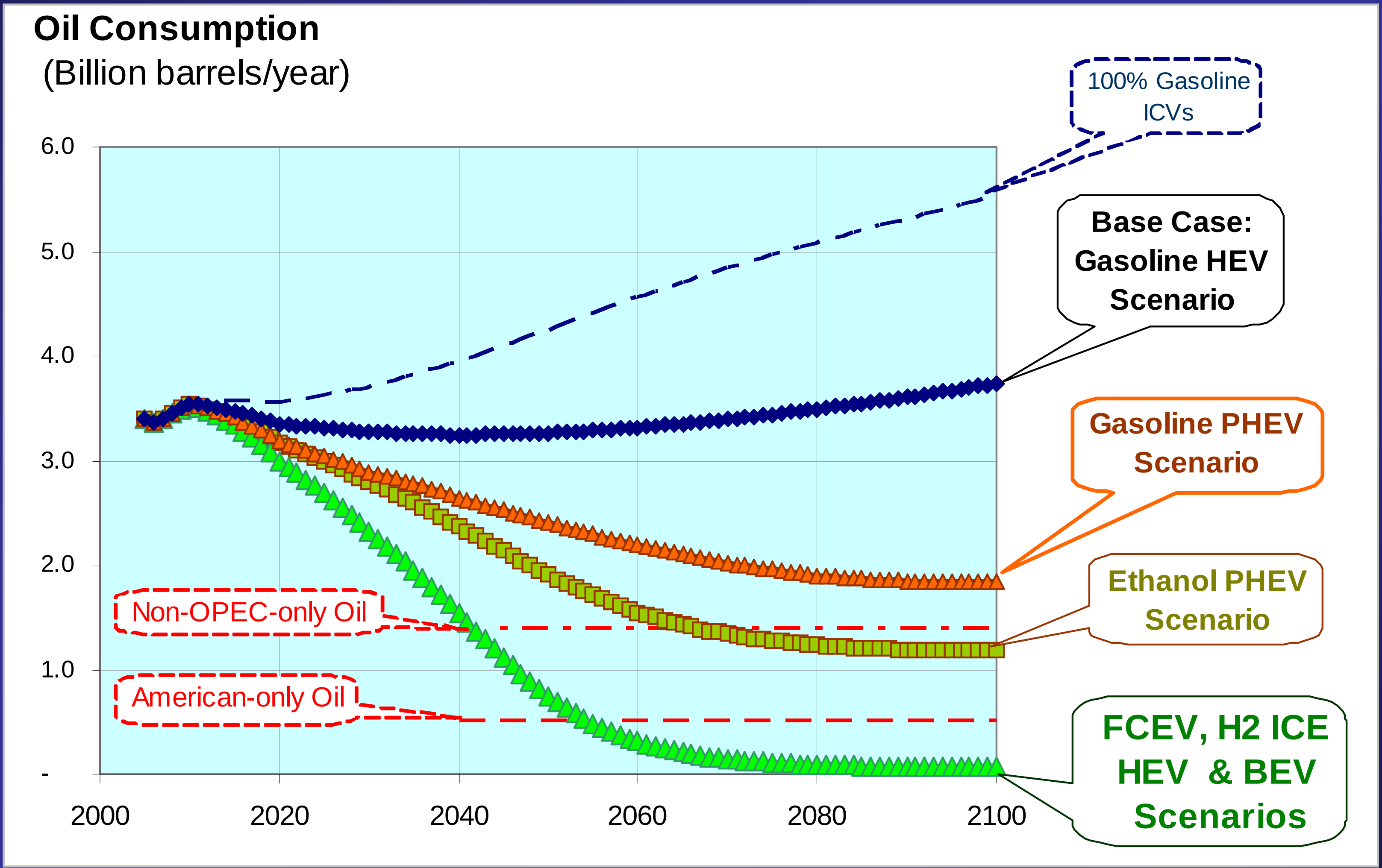

Story Simultaneous.XLS; Tab 'NRC Tables'; W 158 8/19 /2008

# NRC Oil Consumption

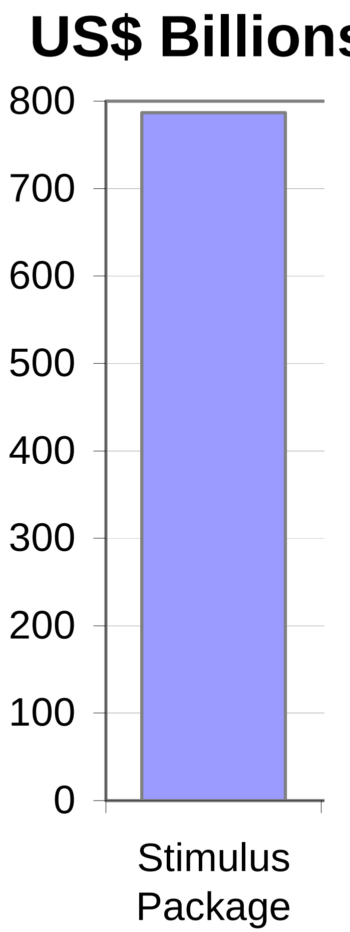


# Oil Consumption: NHA Model with NHA Input Data

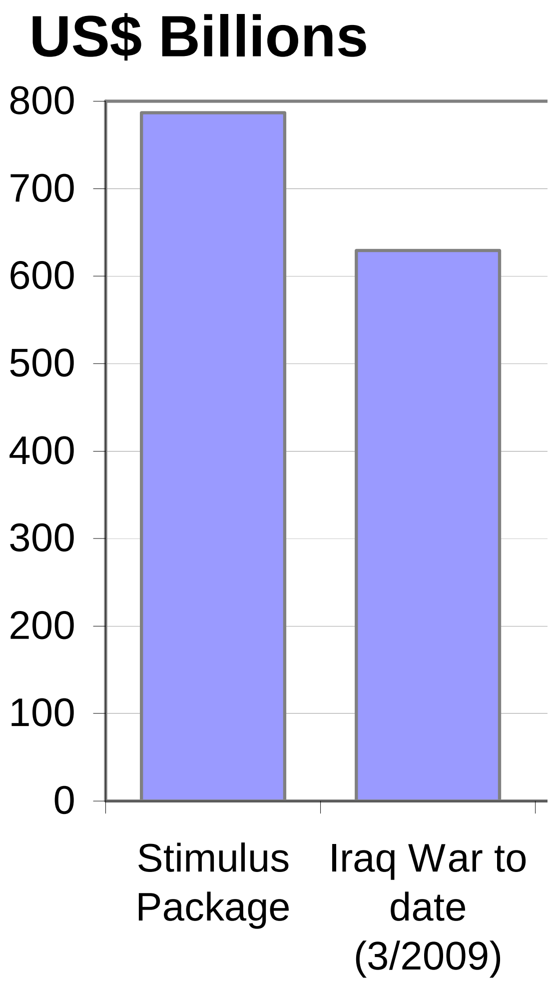
H2Gen



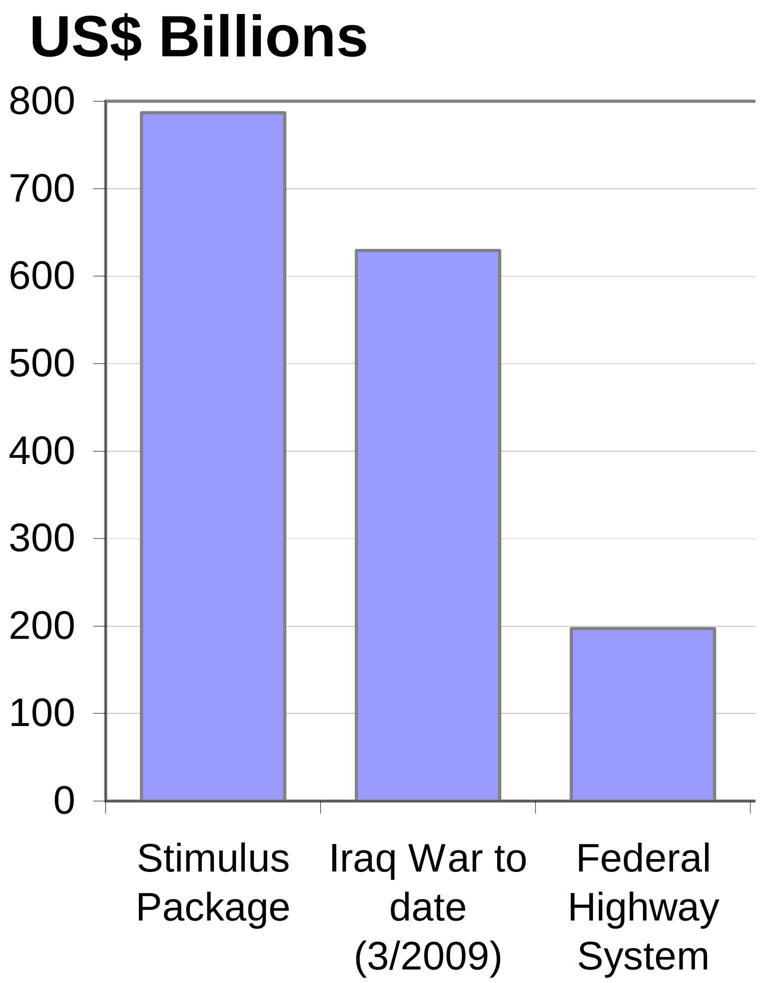
# Hydrogen Infrastructure Costs Compared to Other Projects



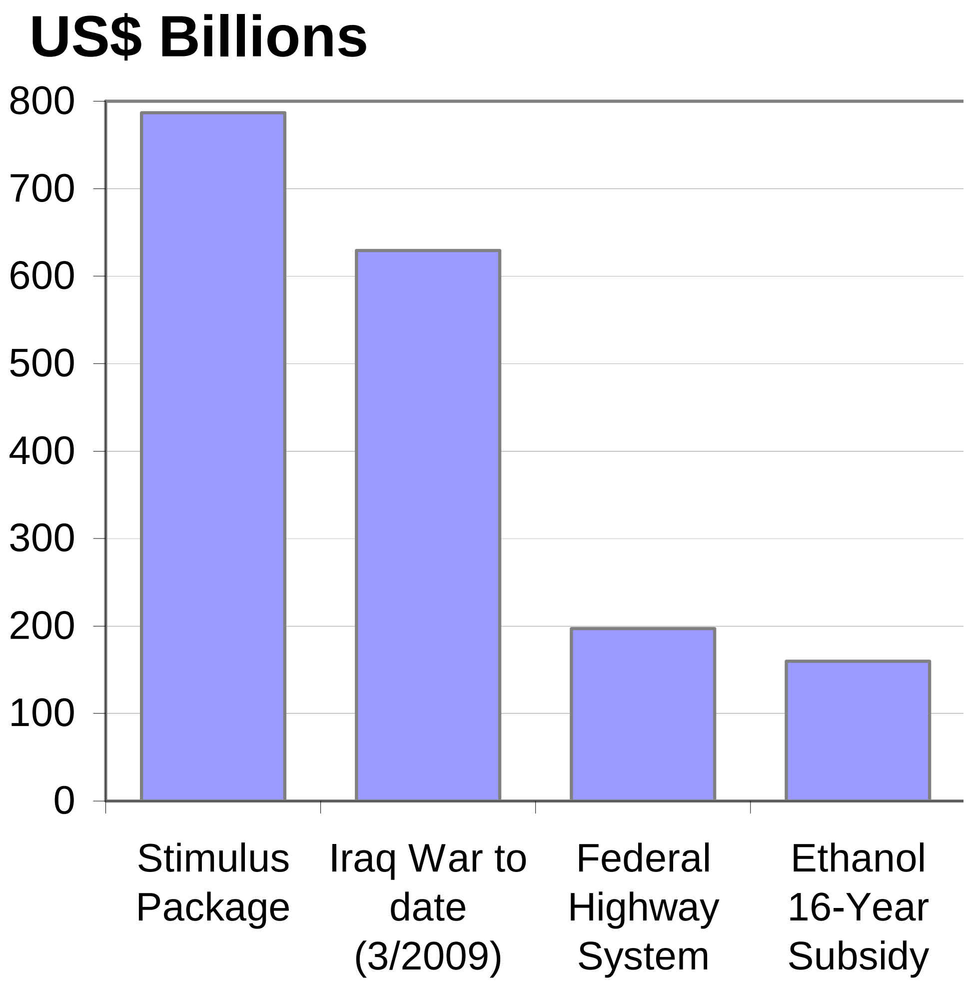
# Hydrogen Infrastructure Costs Compared to Other Projects



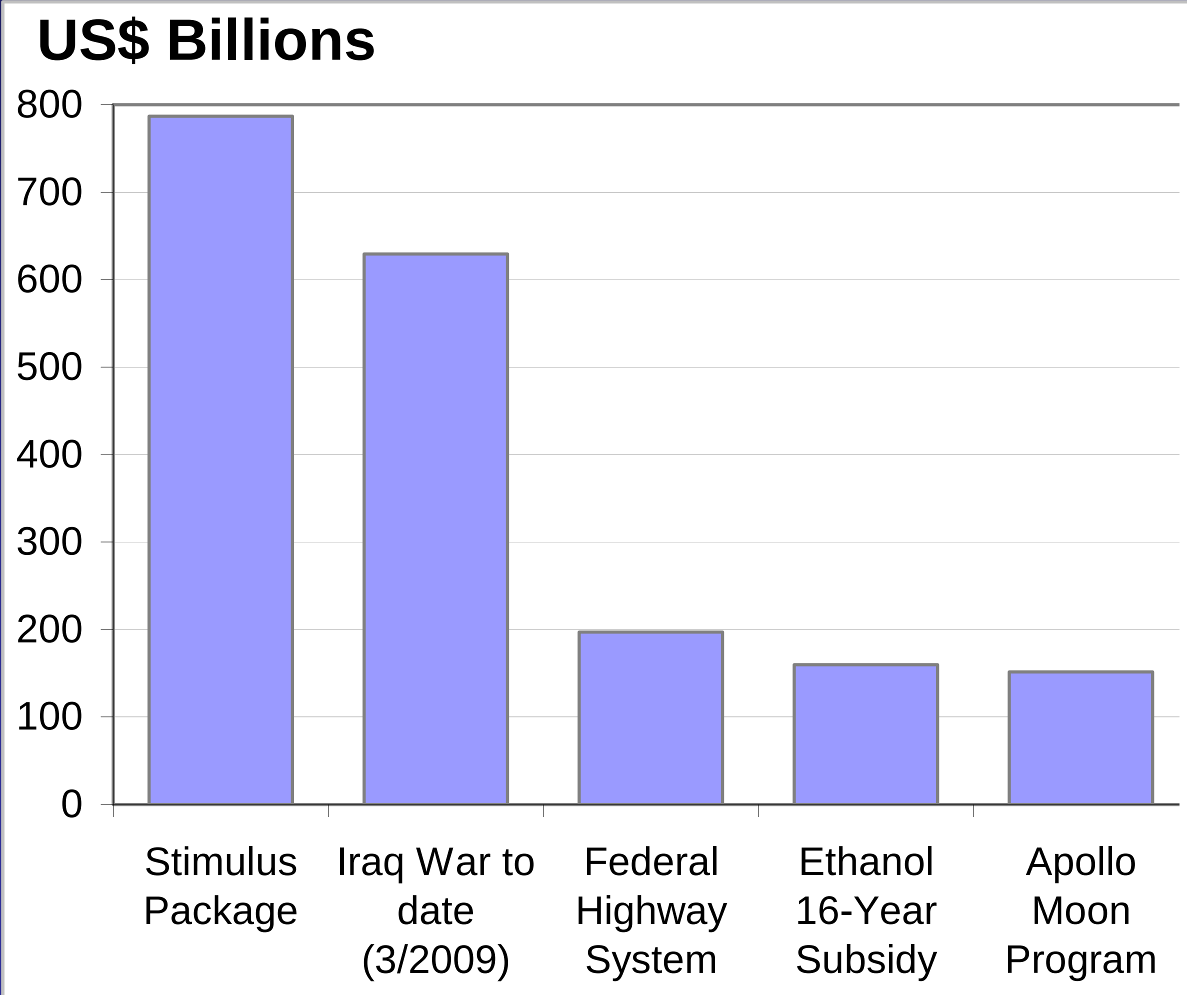
# Hydrogen Infrastructure Costs Compared to Other Projects



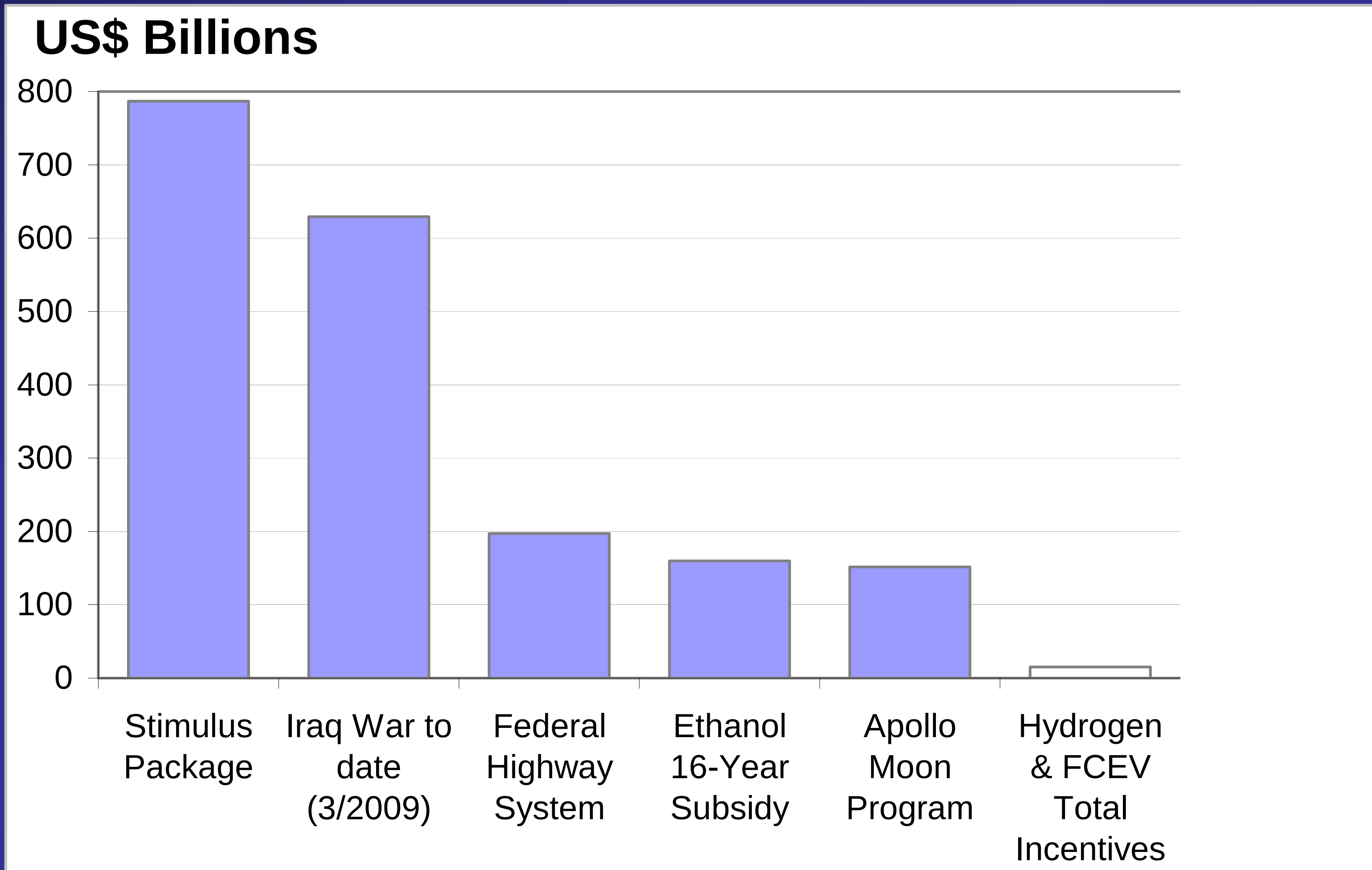
# Hydrogen Infrastructure Costs Compared to Other Projects



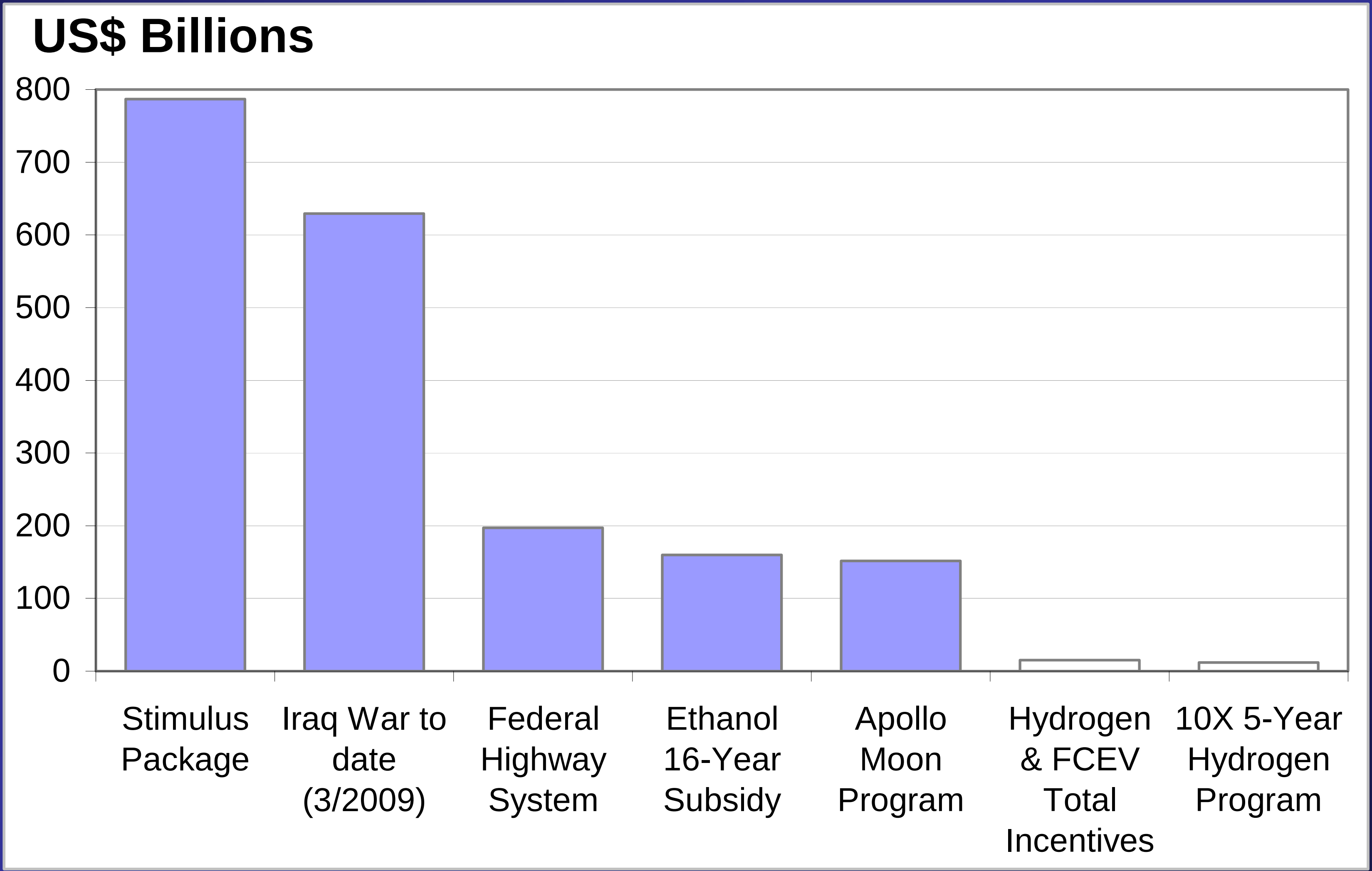
# Hydrogen Infrastructure Costs Compared to Other Projects



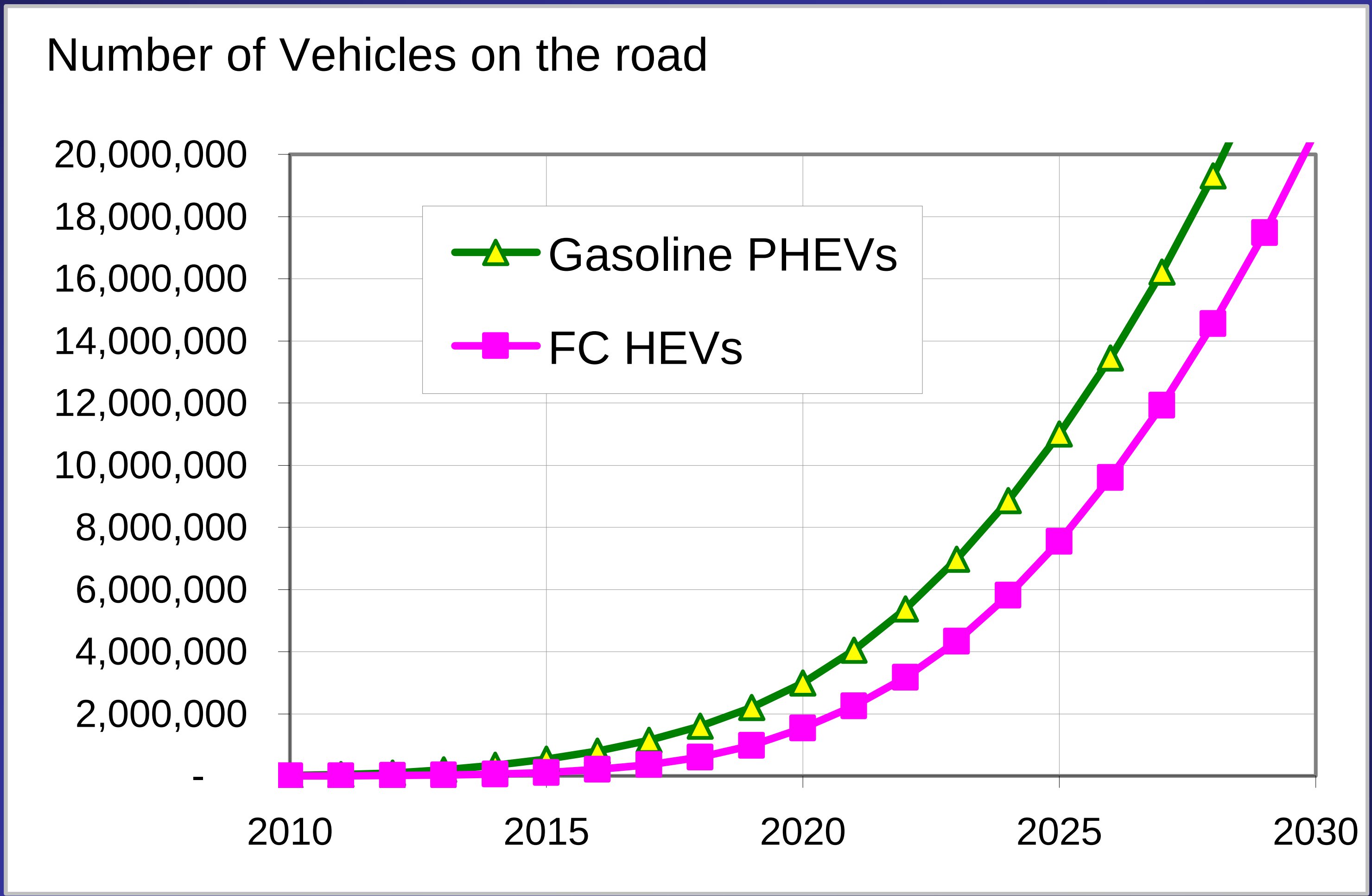
# Hydrogen Infrastructure Costs Compared to Other Projects



# Hydrogen Infrastructure Costs Compared to Other Projects



# Number of Vehicles on the road




Story Simultaneous.XLS; Tab '# Cars'; L 124 5/15 /2009

# How best to use natural gas?

- To produce electricity for battery electric vehicles?
- Or to produce hydrogen for fuel cell electric vehicles?

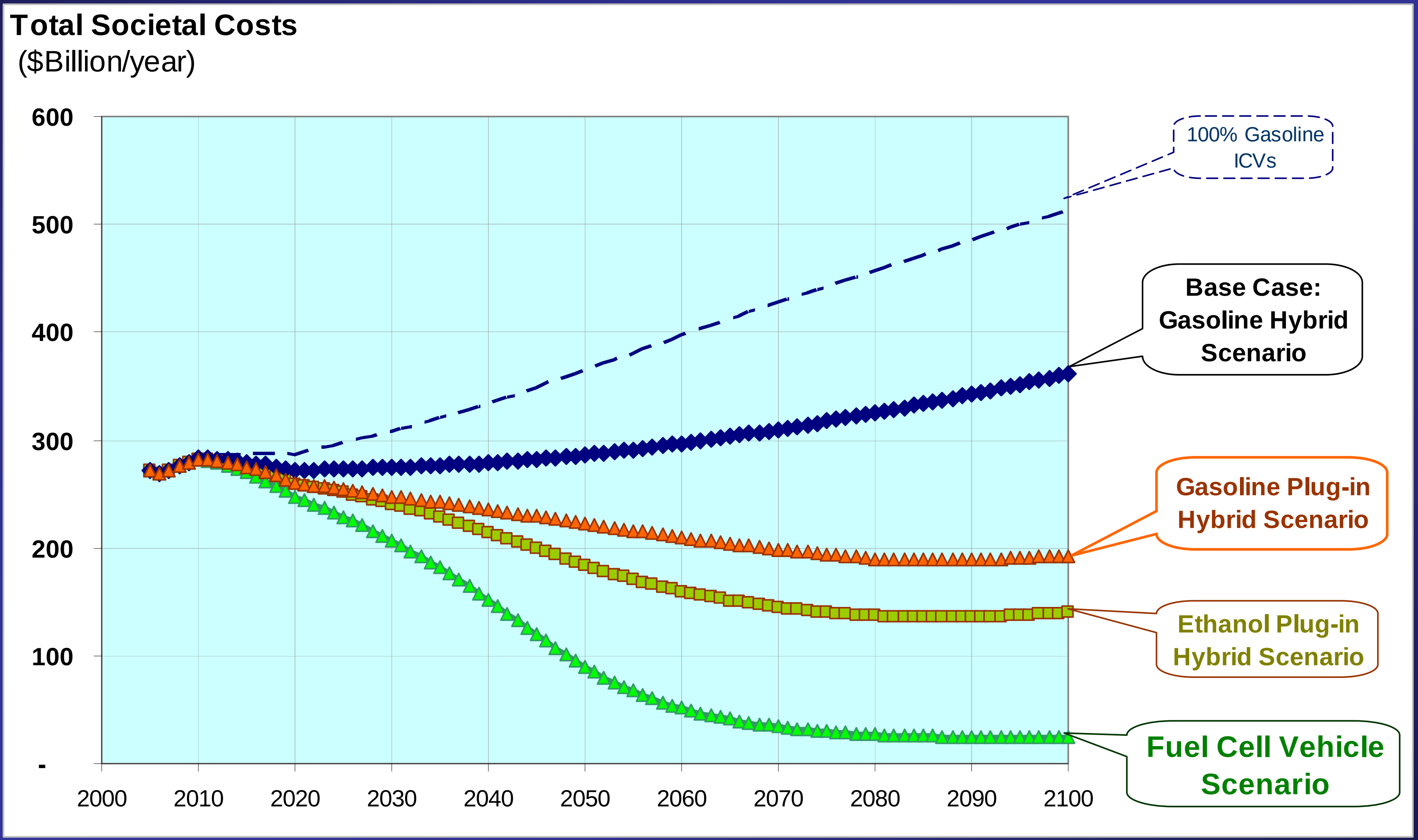
- Backup Topics:
  - Urban air pollution & societal costs
  - Sensitivity studies
  - Natural gas & diesel vehicles

# Financial & Performance Data used in Model

| | |
|---|---|
| SMR HHV efficiency | 78% |
| SMR Electricity Price | $0.095/kWh |
| SMR Electricity Consumption | 1.04 kWh/kg |
| Compression electricity | 2.16 kWh/kg |
| H2 Price Discount | 45% |
| FCV f.e./ICEV f.e. | **2.40** |
| O&M annual Costs | 7% |
| Annual Taxes & Insurance | 2% |
| Marginal income tax (fed & state) | 38.9% |
| Real, after-tax rate of return | **10.0%** |
| Inflation | **1.9%** |
| Analysis Period/Equipment Life (years) | **15** |
| Depreciation period (years) | 7 |
| Depreciation Type* | DB |
| Annual Capital Recovery Factor | 15.5% |

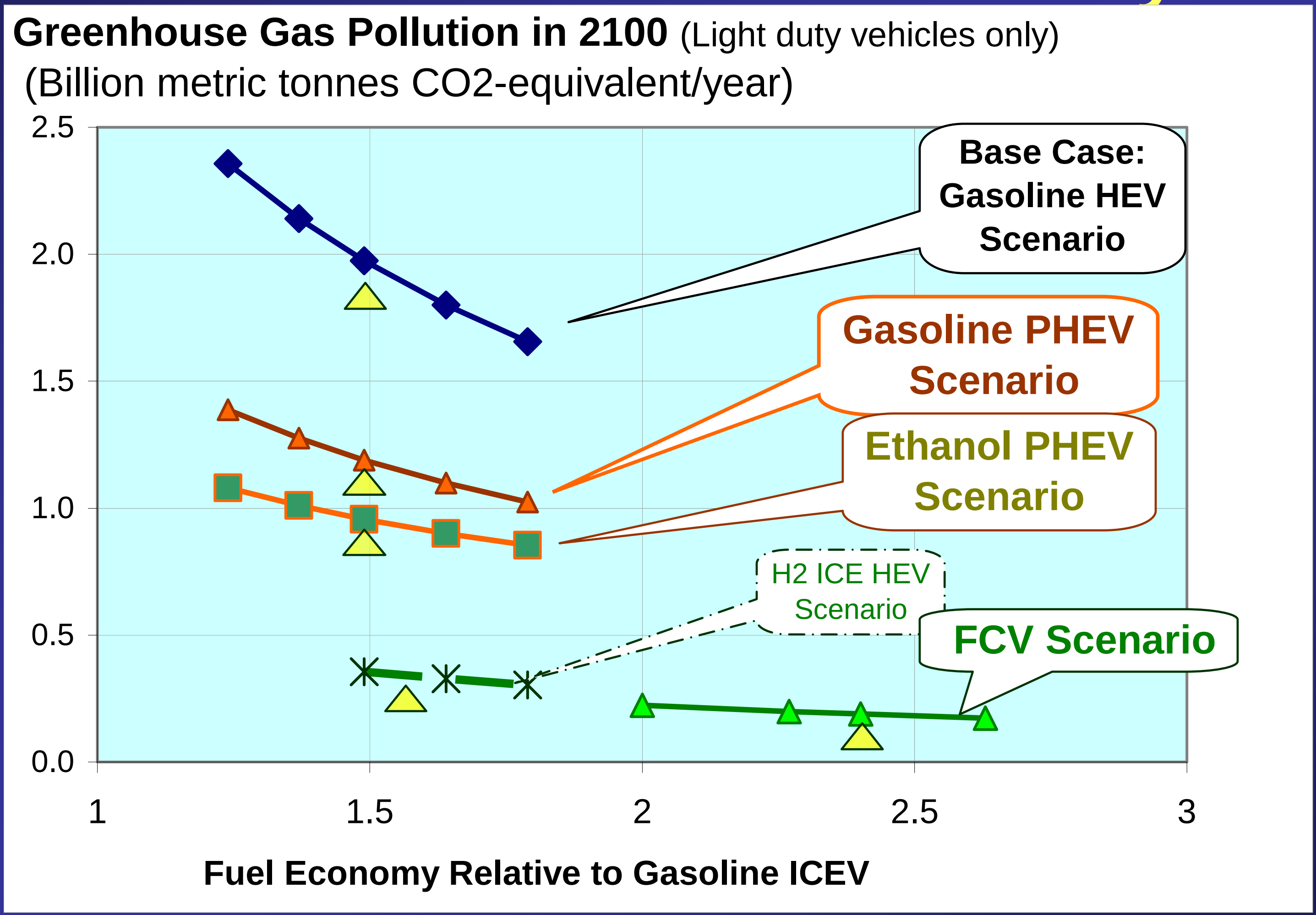
# Total Societal Costs

# Societal Costs from Pollution & Oil Imports



# Sensitivity to Fuel Economy

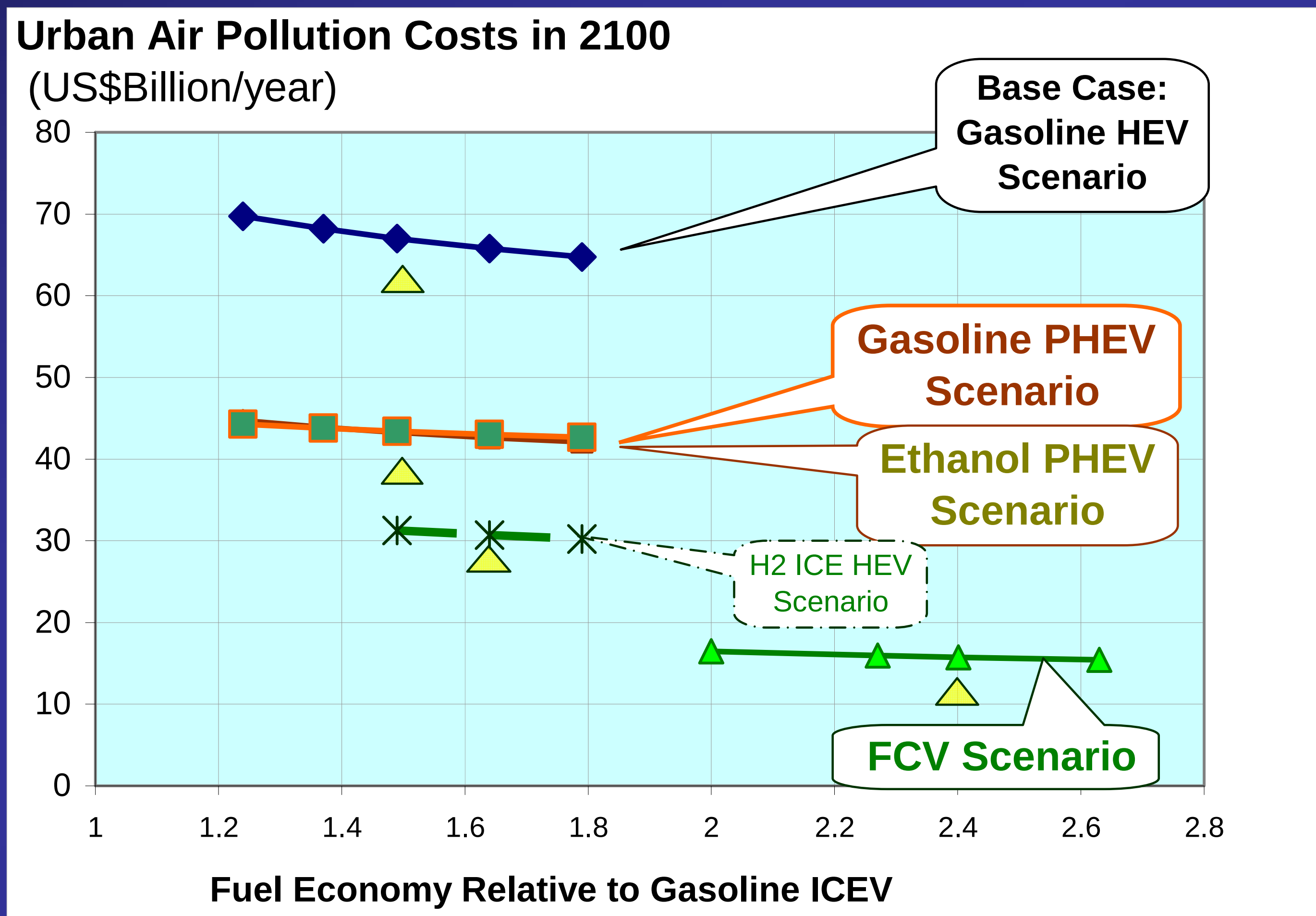
# Greenhouse Gas Sensitivity to Vehicle Fuel Economy




Based on old AEO 2008 data

Story Simultaneous.XLS; Tab 'Sensitivity'; M 51 6/8 /2008

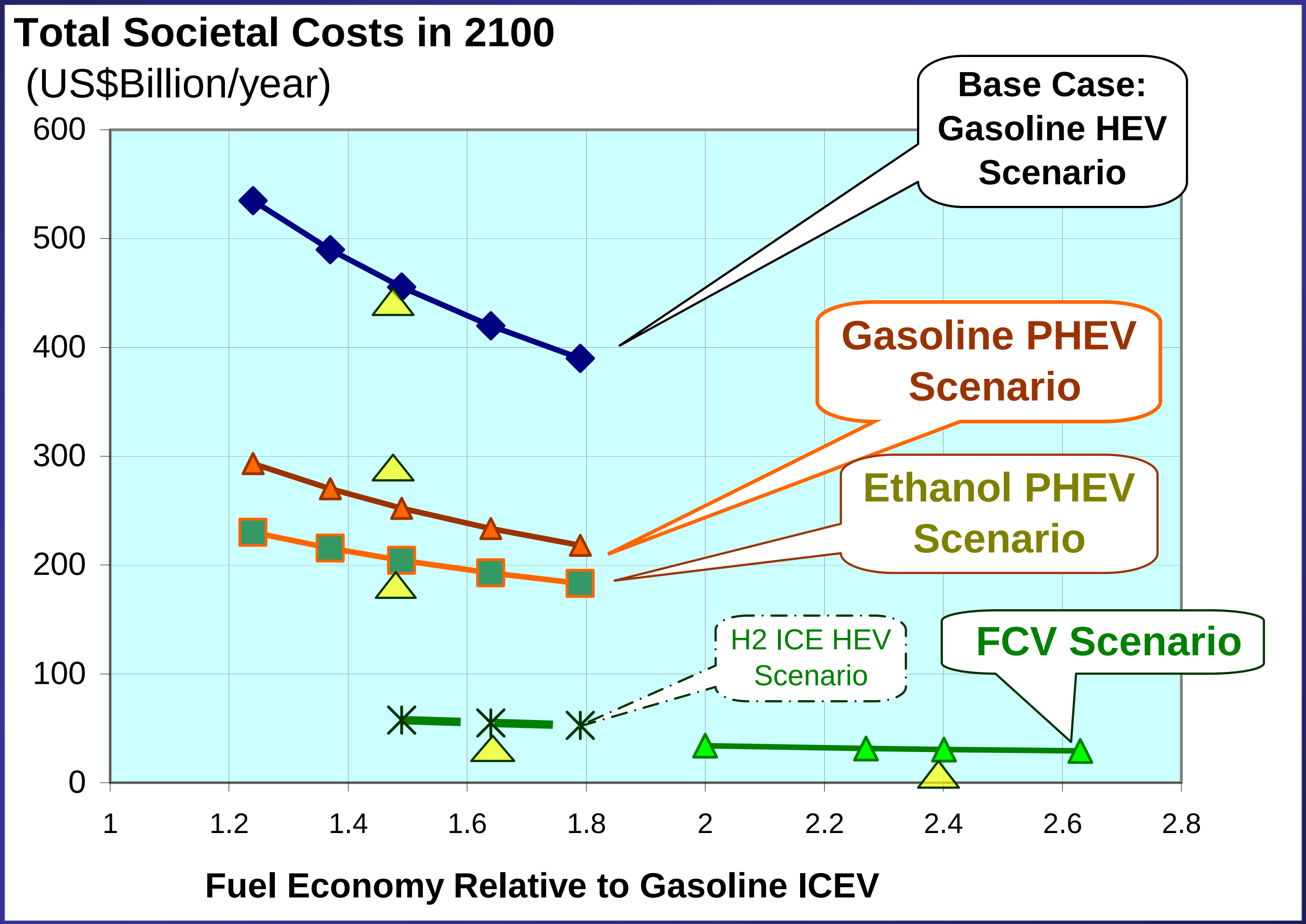
# Urban Air Pollution Sensitivity to Vehicle Fuel Economy




Based on old AEO 2008 data

Story Simultaneous.XLS; Tab 'Sensitivity'; W 51 6/8 /2008

# Societal Cost Sensitivity to Vehicle Fuel Economy

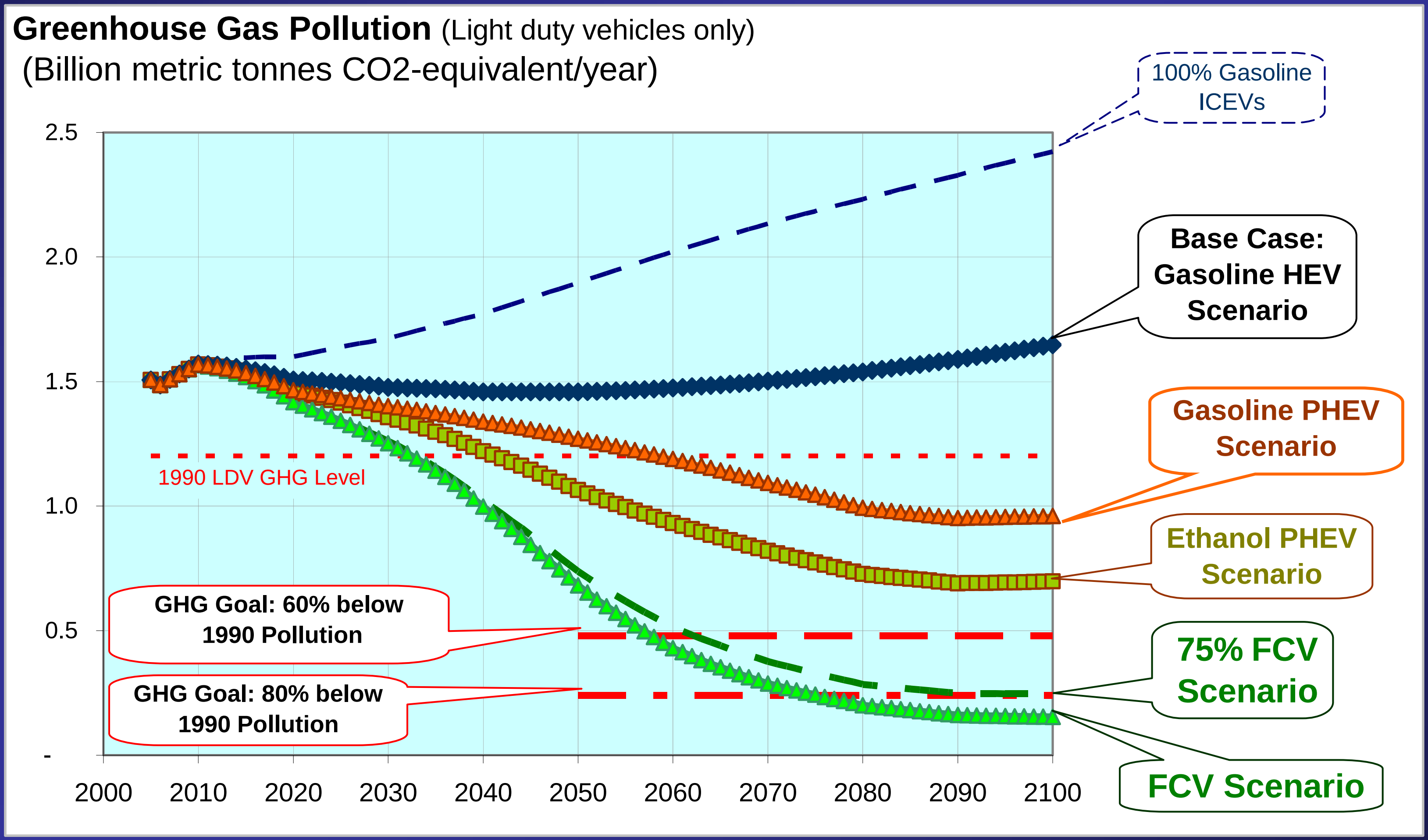



Based on old AEO 2008 data

Story Simultaneous.XLS; Tab 'Sensitivity'; AG 51 6/8 /2008

# Sensitivity to FCEV Market Share & Carbon Footprints

# Greenhouse Gases with 75% FCEV Market Limit

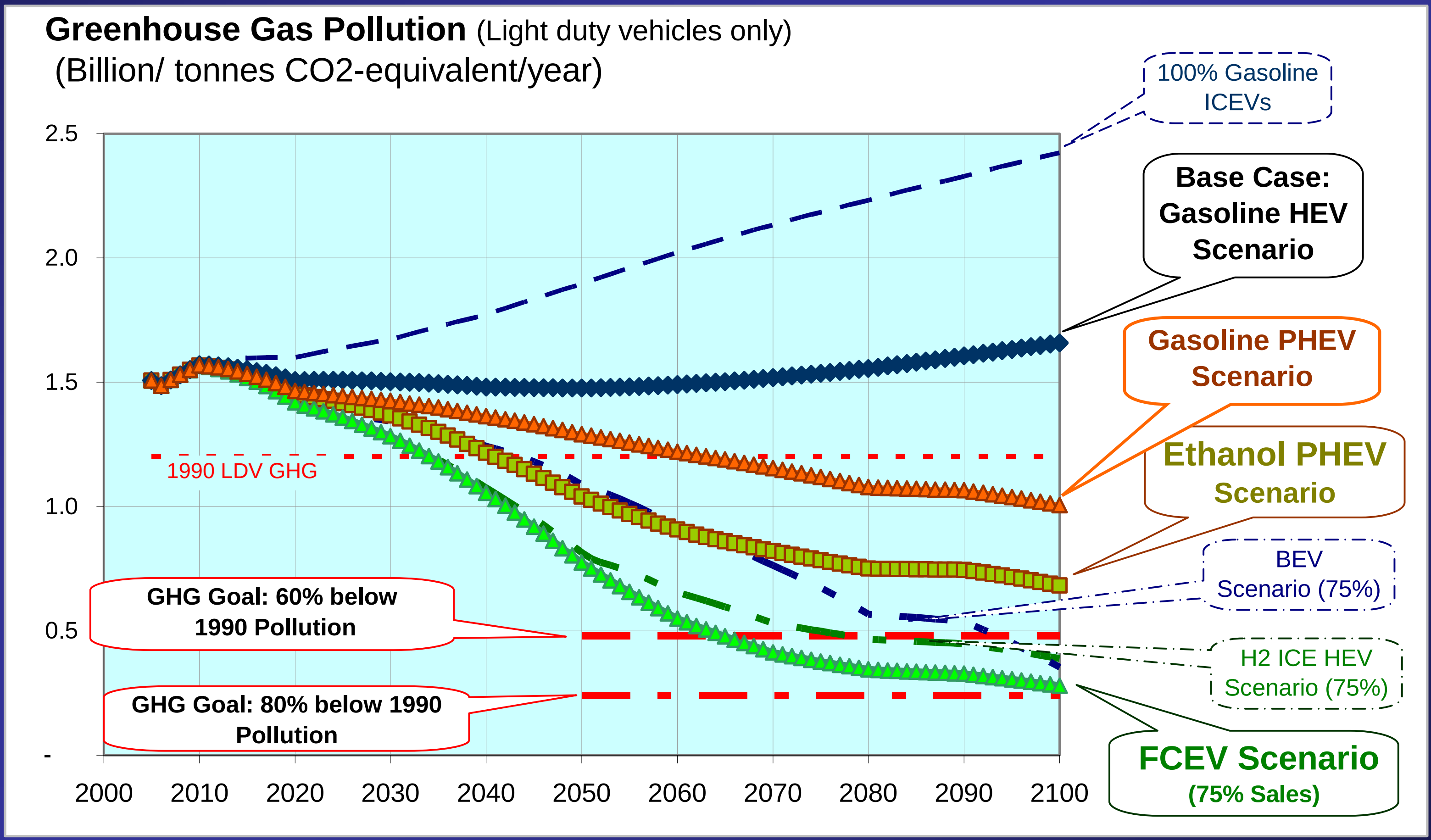



Story Simultaneous.XLS; Tab 'Graphs'; AN 34 2/16 /2009

# Greenhouse Gases

## with 75% FCEV Limit & DOE Carbon parameters

(Greener grid and less green hydrogen; all-electric CD mode for PHEVs)

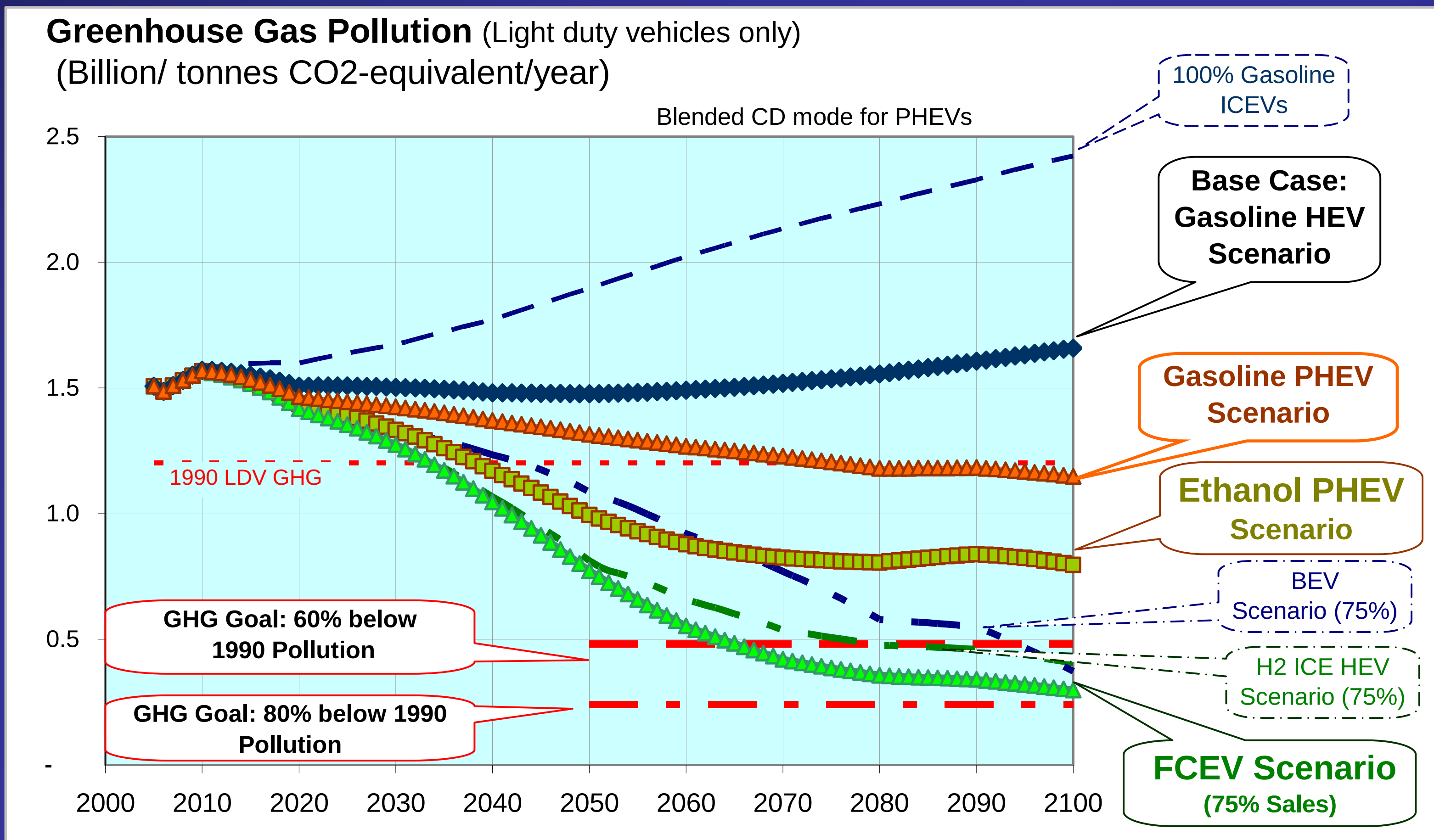



Story Simultaneous.XLS; Tab 'Graphs'; AD 529 2/16 /2009

# Greenhouse Gases

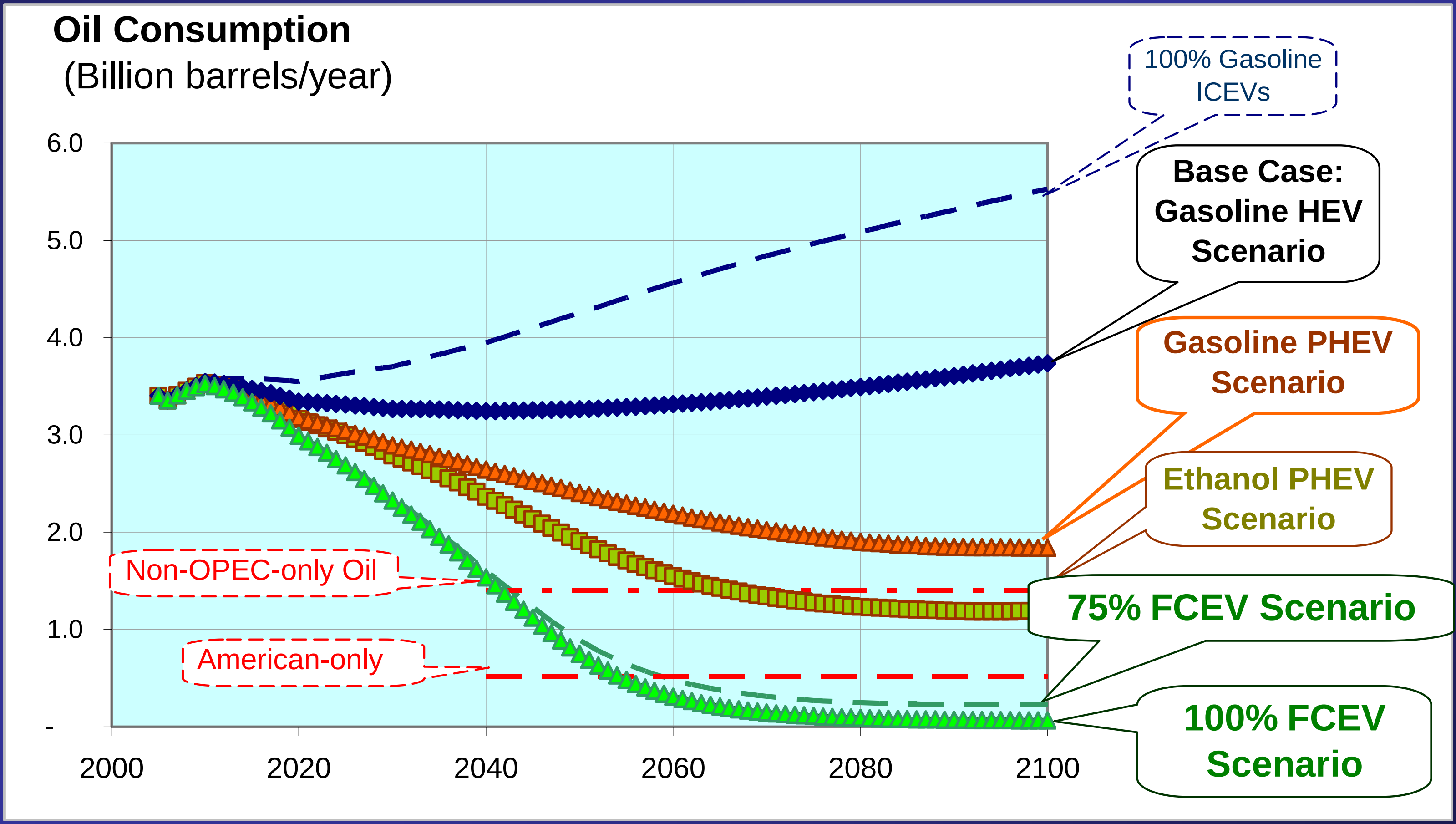
## with 75% FCEV Limit & DOE Carbon parameters

(Greener grid and less green hydrogen & Blended CD mode for PHEVs)




Story Simultaneous.XLS; Tab 'Graphs'; AD 561 2/16 /2009

# Oil Consumption with 75% FCEV Market Limit

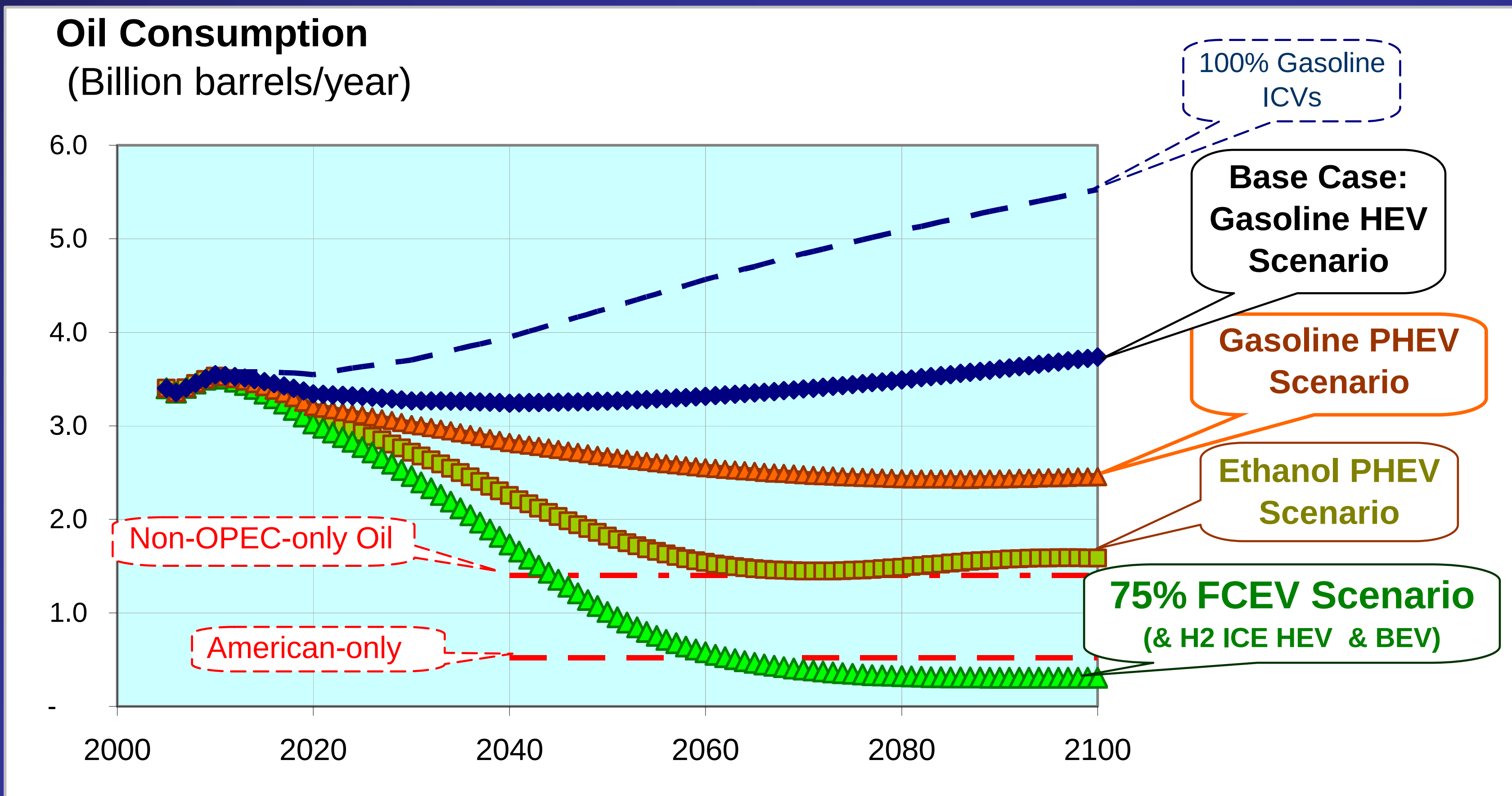





Story Simultaneous.XLS; Tab 'Graphs'; AD 180 2/16 /2009

# Oil Consumption

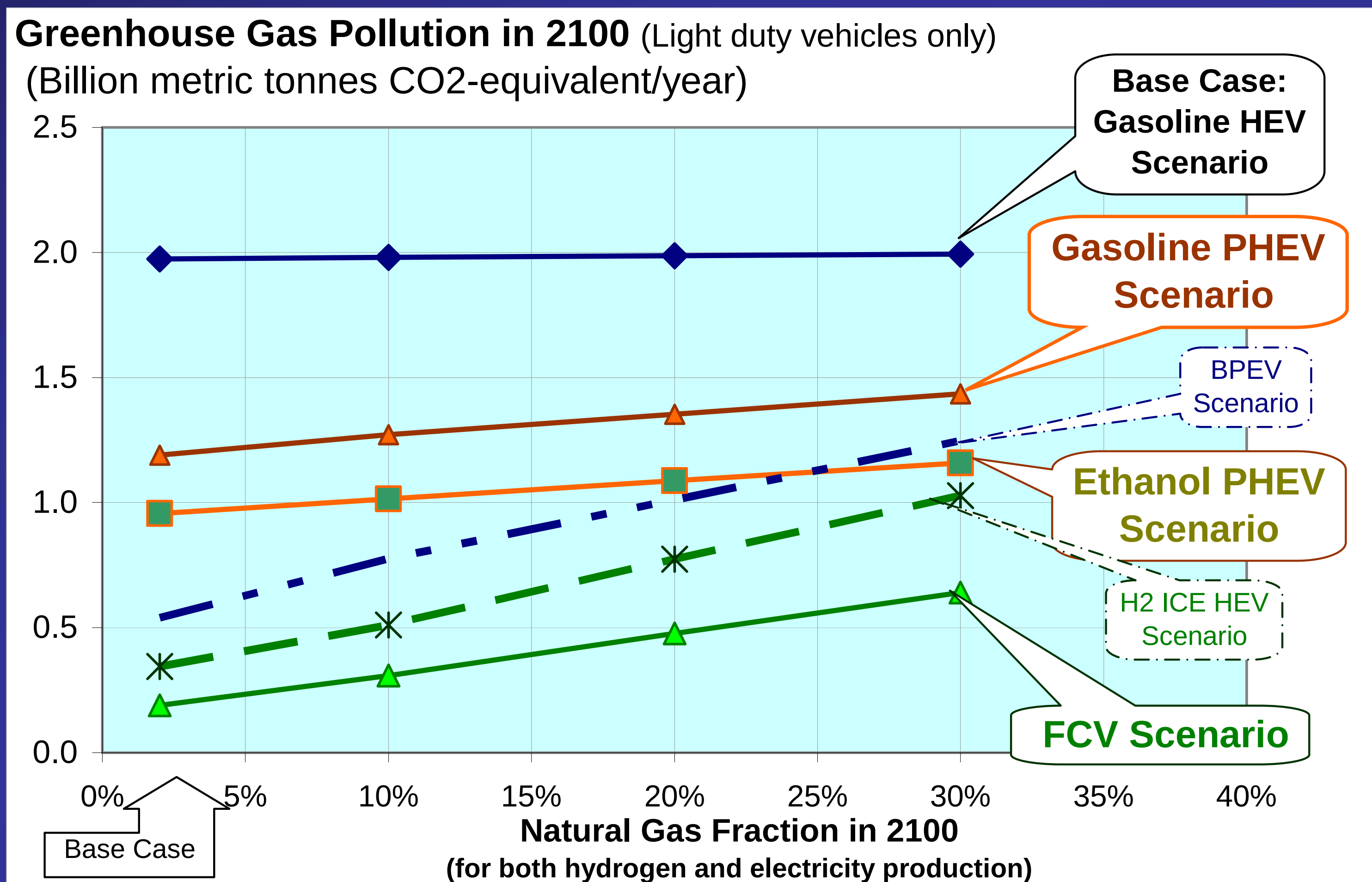
## with 75% FCEV Limit & DOE Carbon parameters
## (Greener grid and less green hydrogen)






Story Simultaneous.XLS; Tab 'Graphs'; AD 235 2/16 /2009

# GHG Sensitivity to NG Fraction
## (electricity & hydrogen source)

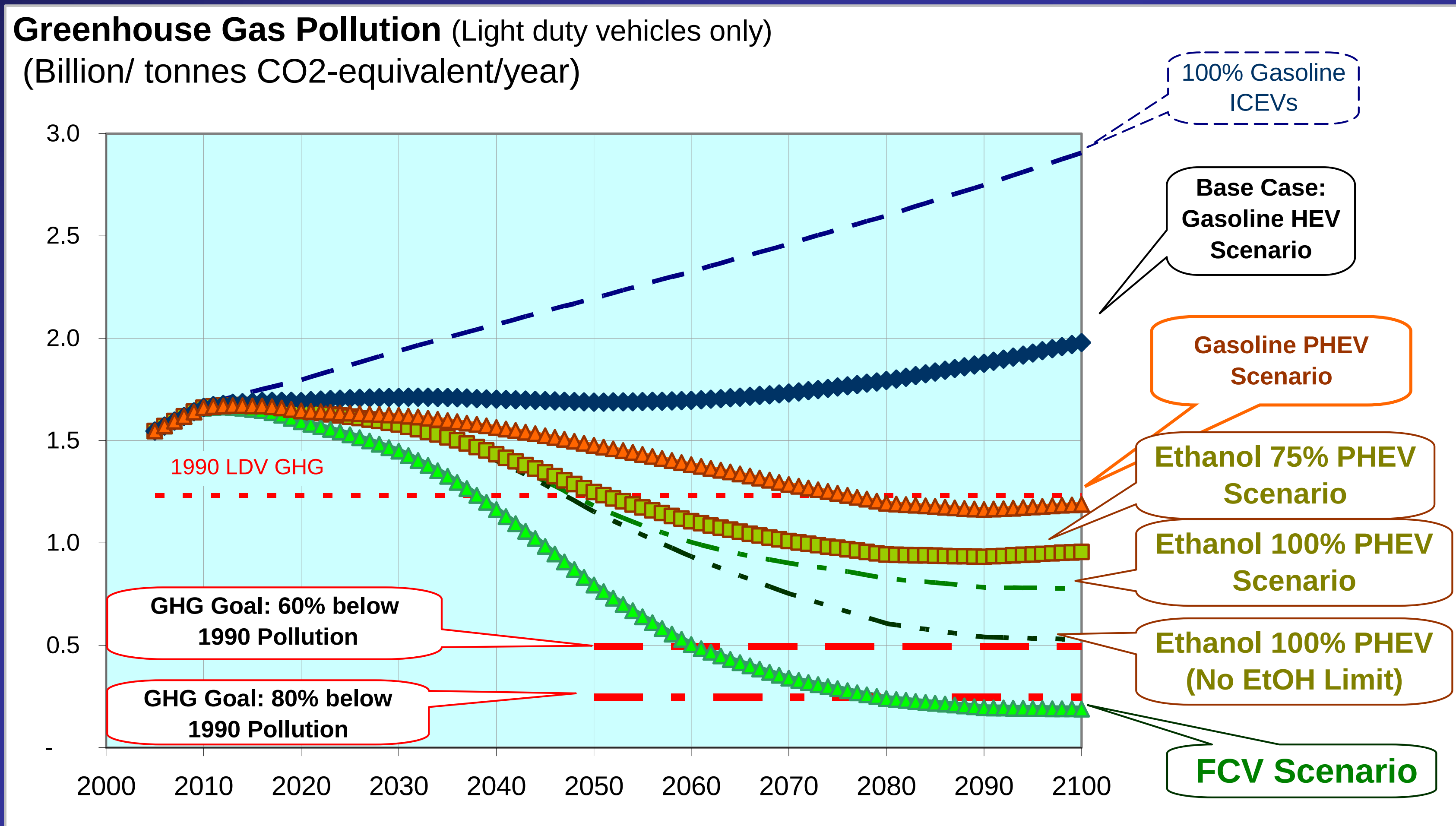



Based on old AEO 2008 data

Story Simultaneous.XLS; Tab 'Sensitivity'; M 91 6/8 /2008

# Sensitivity to Ethanol PHEV Market share

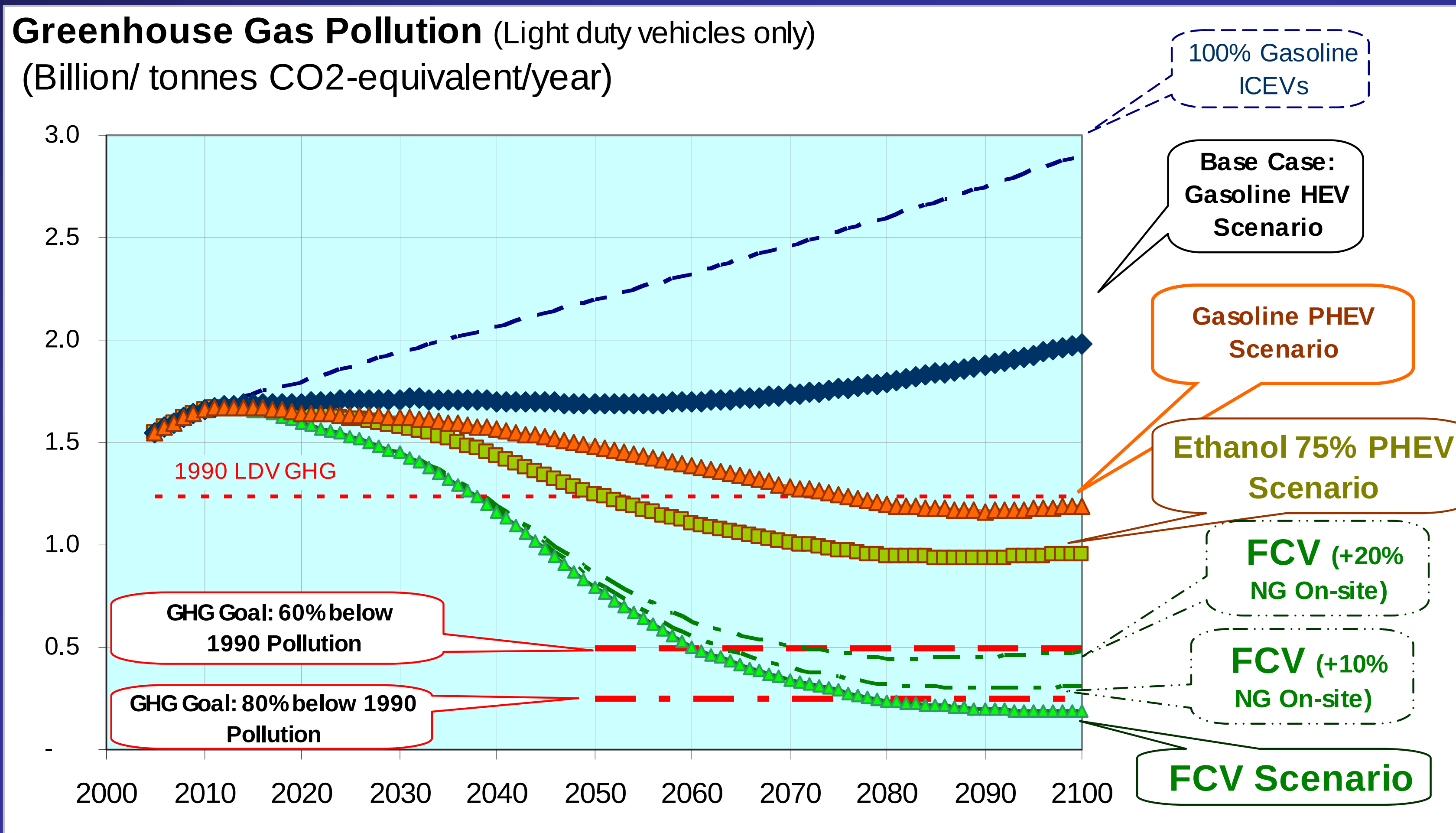
# GHG Sensitivity to Ethanol Production Capacity & Plug-in Capacity




Based on old AEO 2008 data

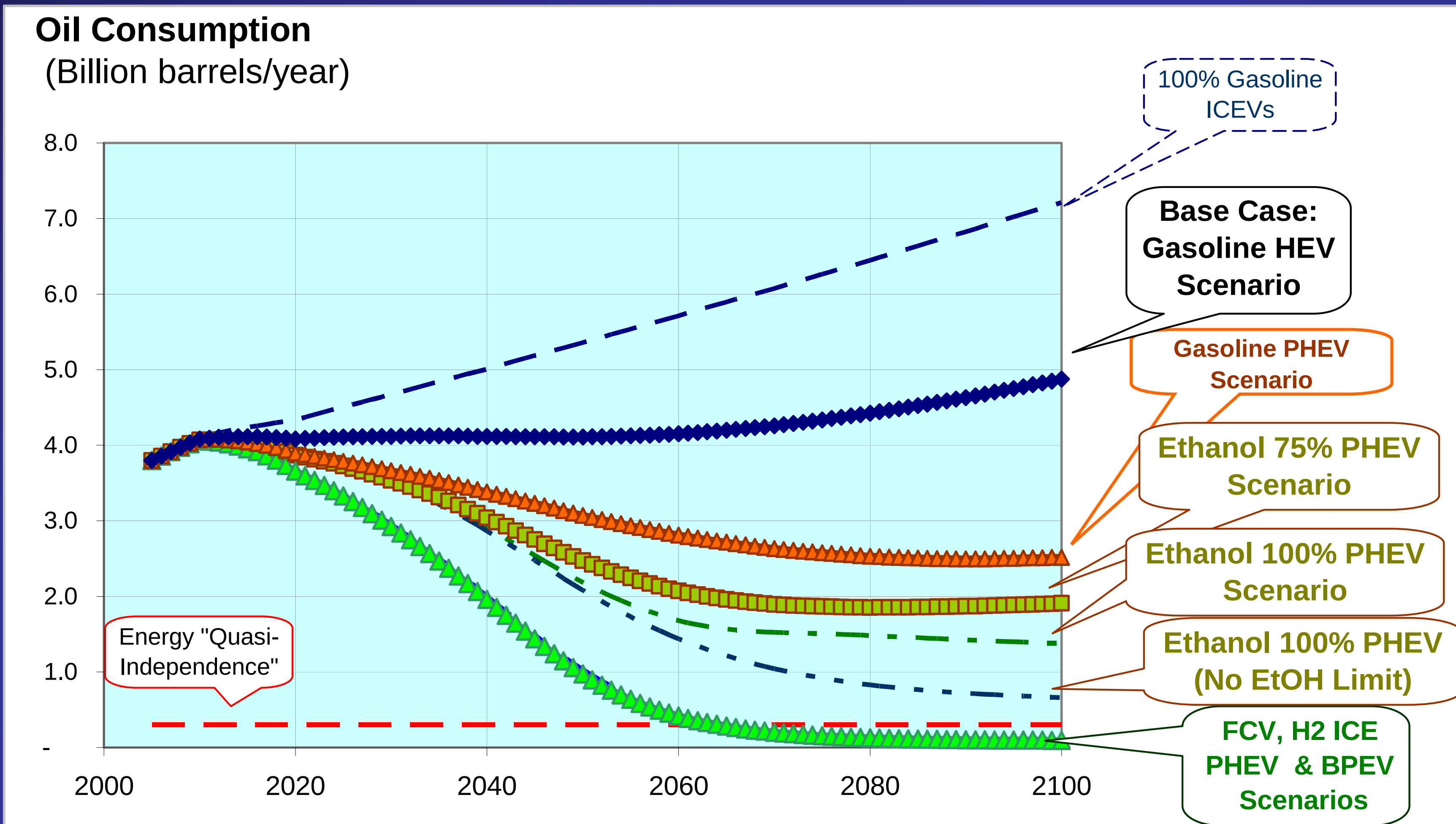
Story Simultaneous.XLS; Tab 'Graphs'; AN 405 5/25 /2008

# GHG Sensitivity to Hydrogen Source




Based on old AEO 2008 data

# Oil Consumption Sensitivity to Ethanol Production & Plug-in Capacity



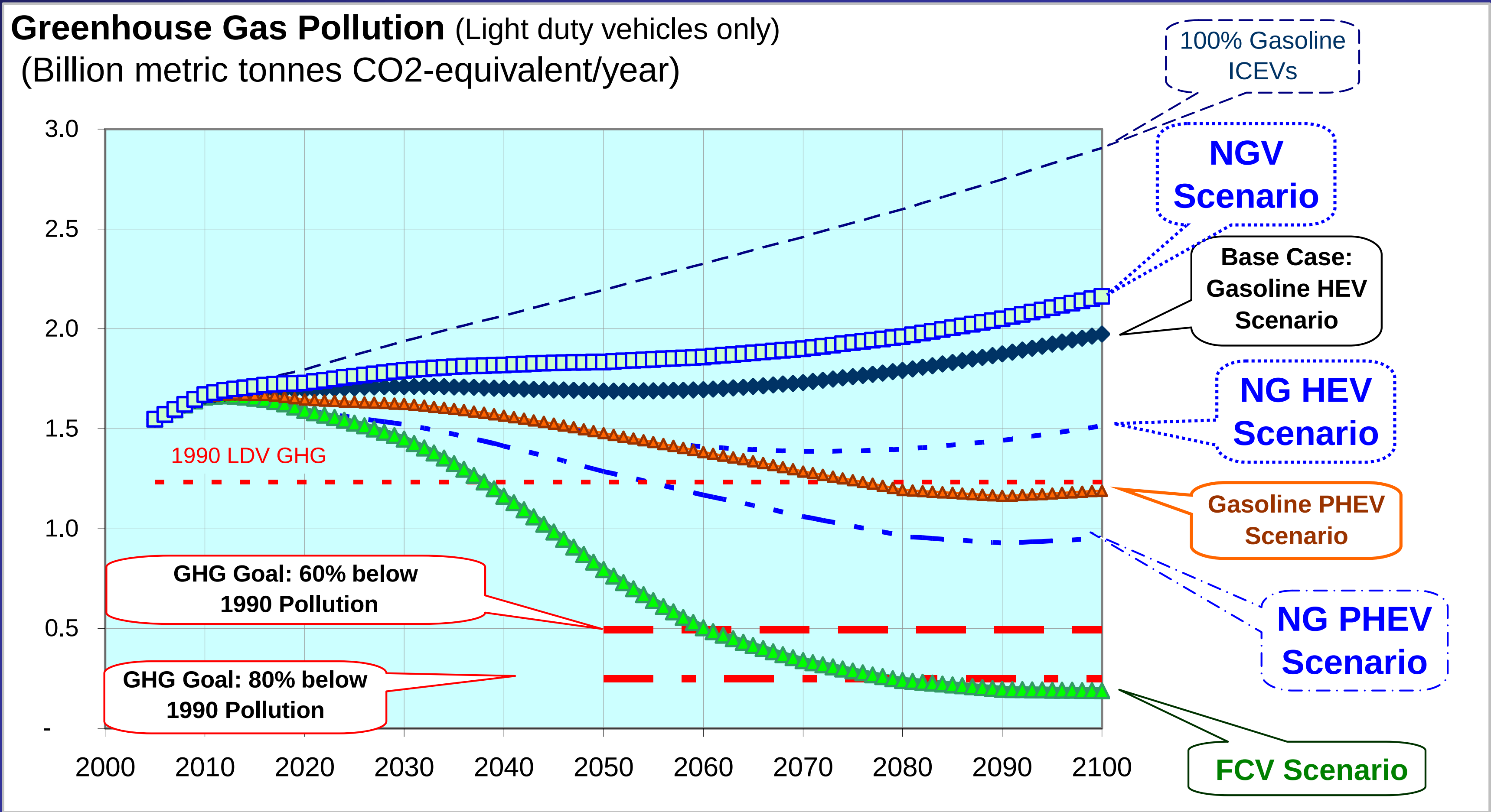

Based on old AEO 2008 data

Story Simultaneous.XLS; Tab 'Graphs'; AD 122 5/25 /2008

# Backup Slides

- Natural Gas Vehicles
- Diesel CIDI Vehicles

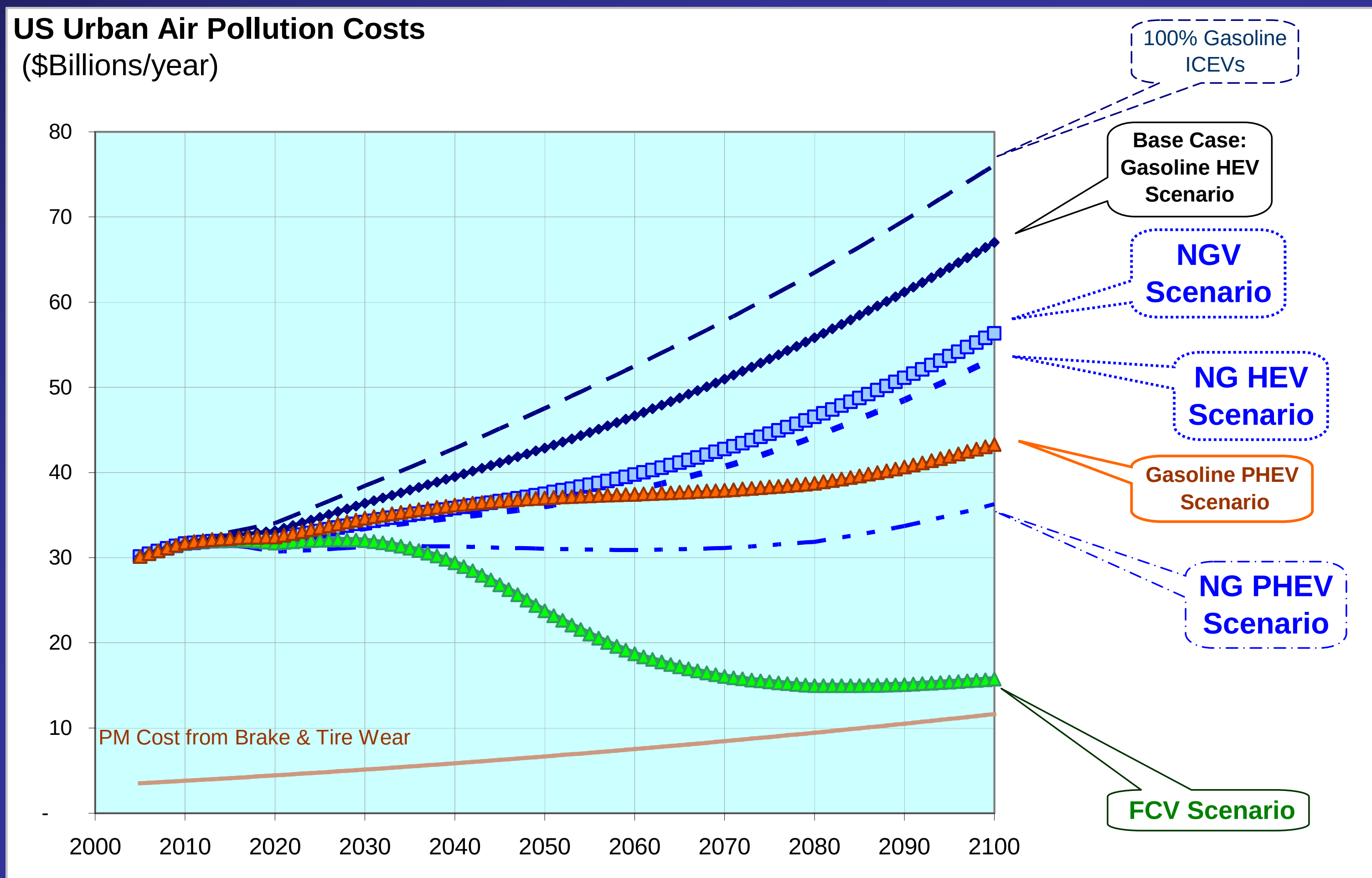
# Greenhouse Gases with Natural Gas Vehicles




Based on old AEO 2008 data

Story Simultaneous.XLS; Tab 'Graphs'; BC 495 9/8 /2008

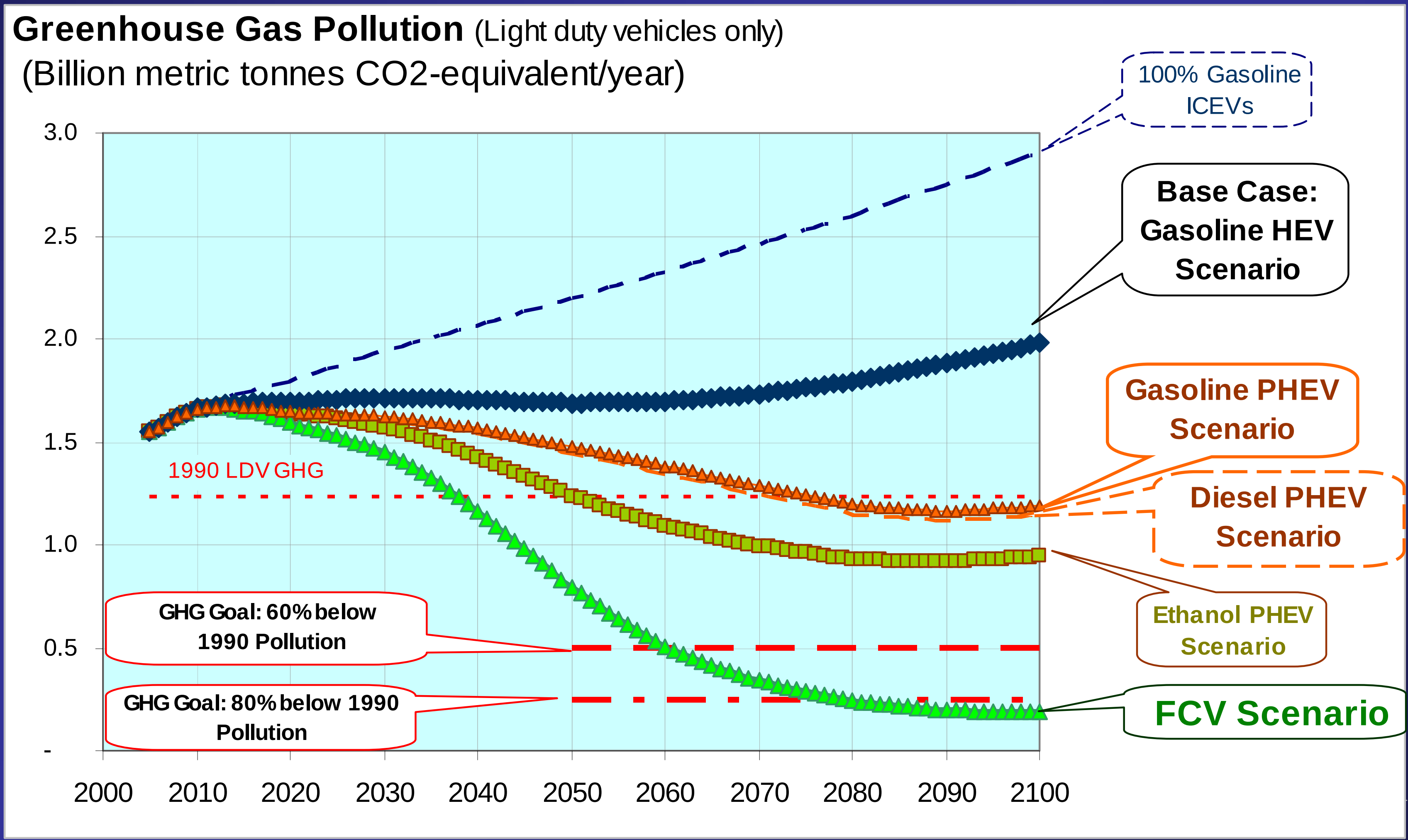
# Urban Air Pollution with Natural Gas Vehicles





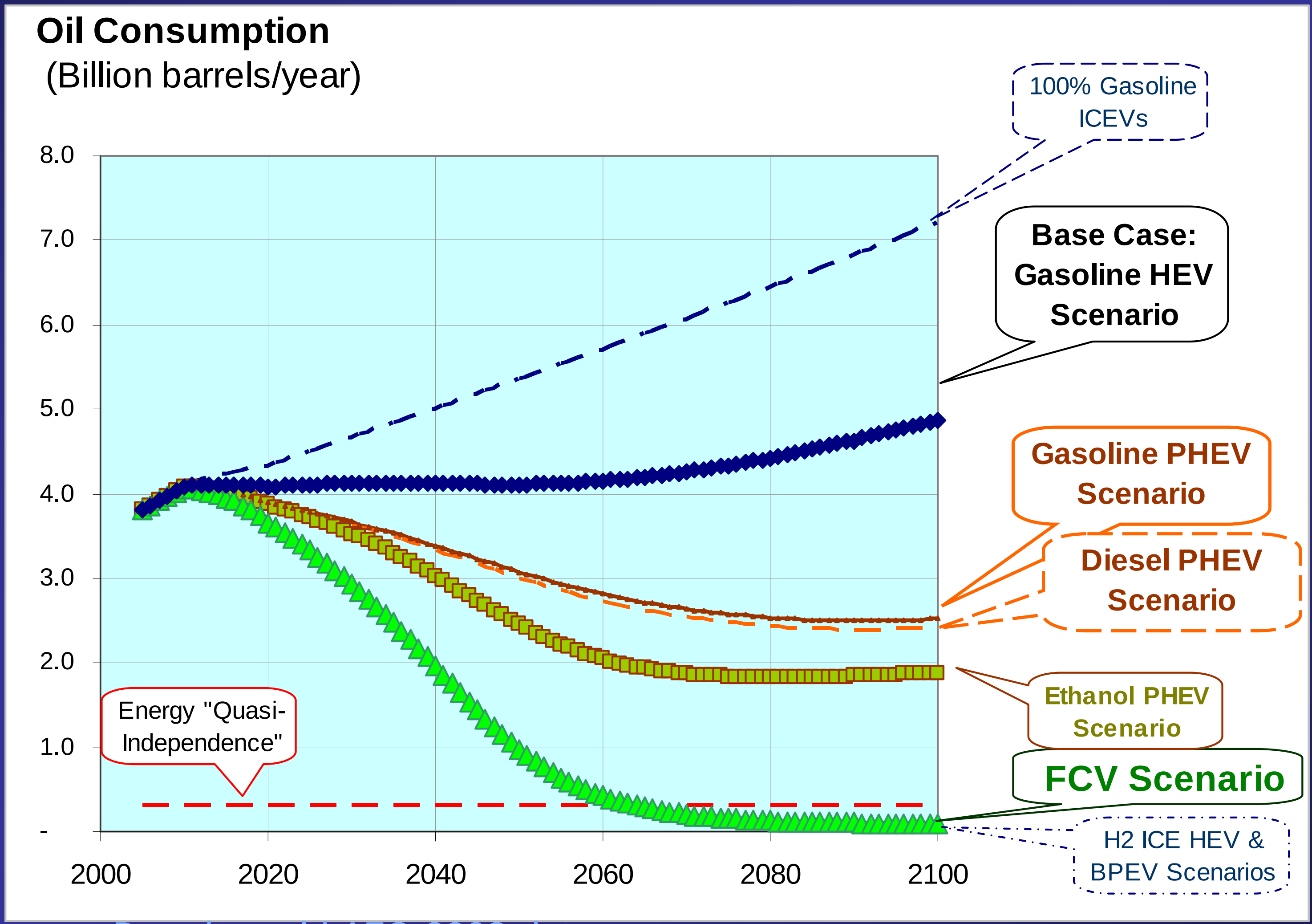

Story Simultaneous.XLS; Tab 'Graphs'; DF 102 9/8 /2008

# Diesel PHEV GHGs



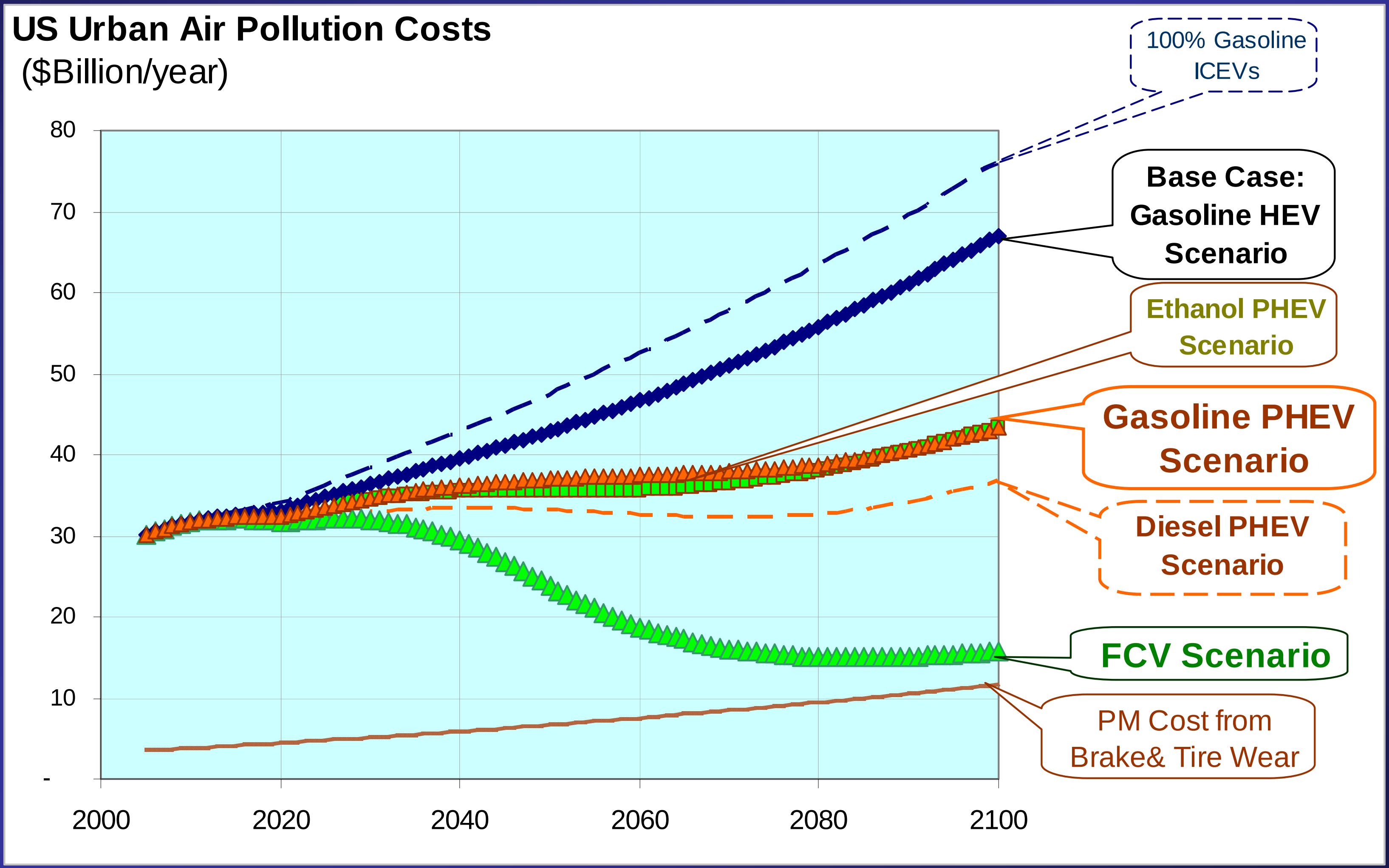

Based on old AEO 2008 data

# Diesel PHEV Oil Consumption




Based on old AEO 2008 data

# Diesel PHEV Urban Air Pollution




Based on old AEO 2008 data

# NGV vs. FCV

## (Hydrogen from natural gas)

**Natural Gas** →

**Natural Gas Reformer**
Efficiency
75%

→ **$H_2$** →

Hydrogen
**Compression & Storage**
Efficiency
93.9%
(200psi to 6,250 psi)

→

**Fuel Cell Vehicle**
Efficiency
20 X 2.45 = 48.9 mpg

Natural gas efficiency: 0.75 x 0.939 X 48.9 = 34.4

**Natural Gas** →

Natural Gas
**Compression & Storage**
Efficiency
96.4%
(15 psi to 3,600 psi)

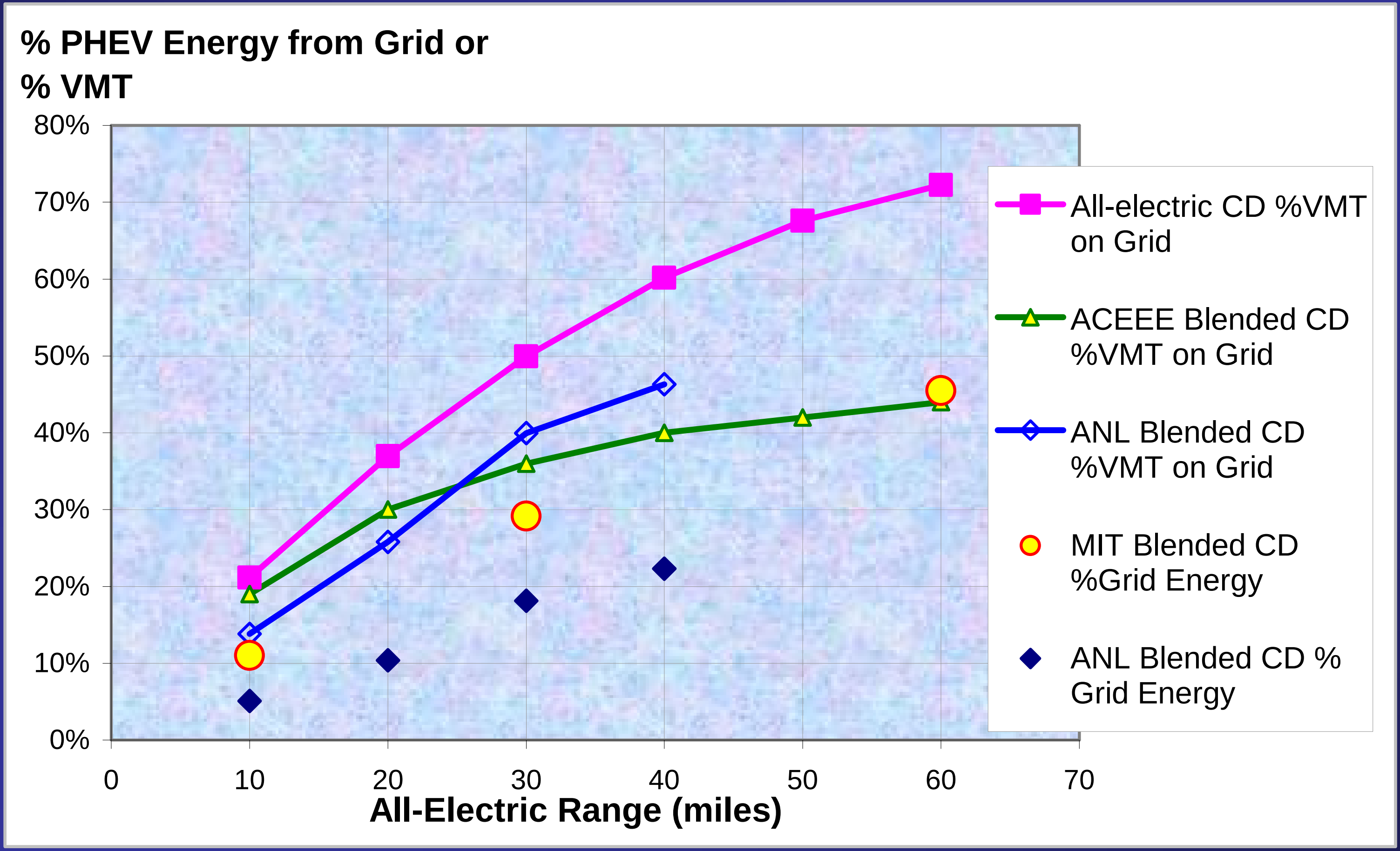
→

**ICE Vehicle**
Efficiency
20 mpg

Natural gas efficiency: 0.964 x 20 = 19.3

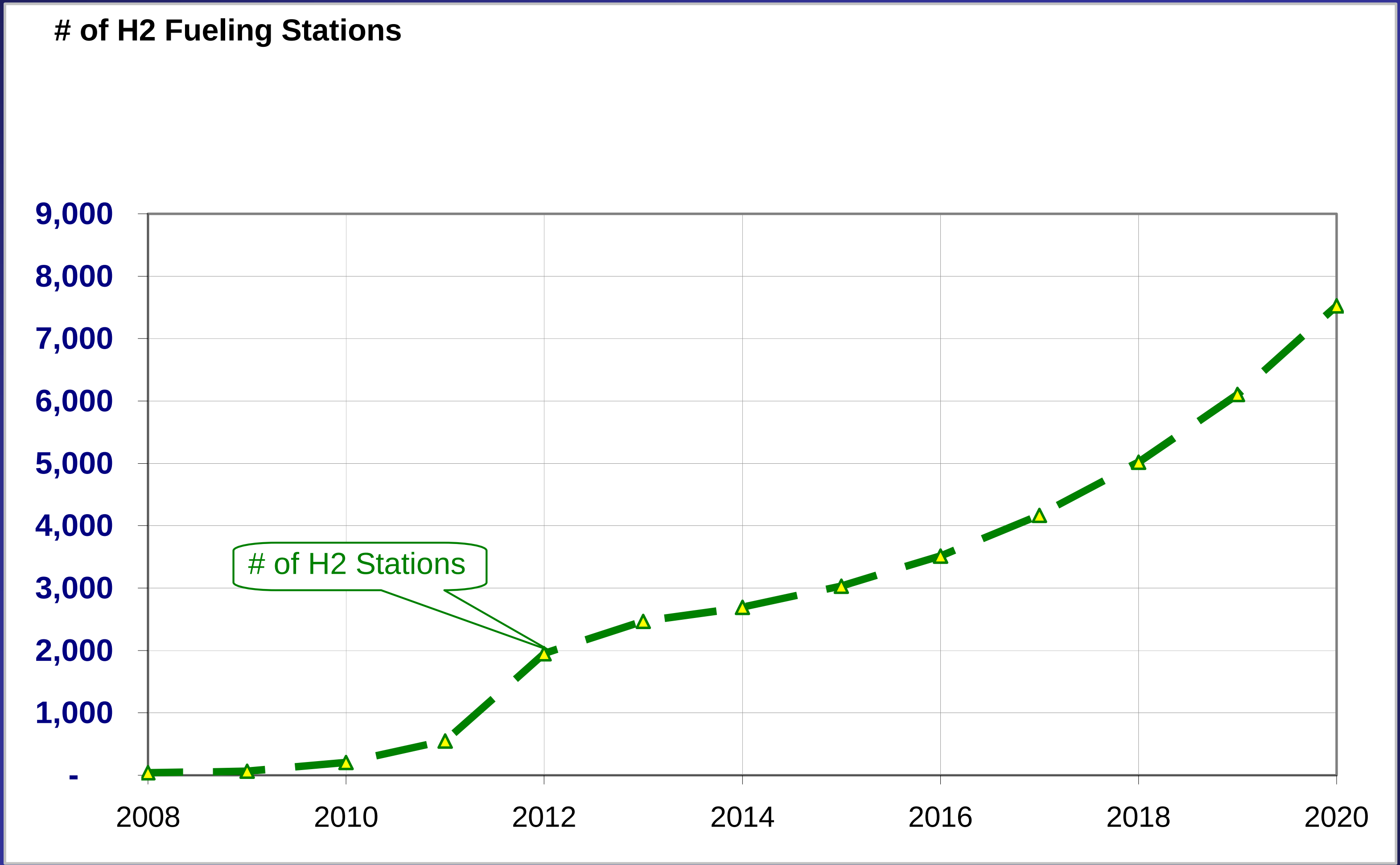
| | |
|---|---|
| **FCV Advantage:** | **1.79** |
| **FCV GHG / ICEV GHG** | **56% (44% GHG reduction)** |

# Blended Charge Depleting Mode




Story Simultaneous.XLS; Tab 'Blended CD'; AE 61 2/17 /2009

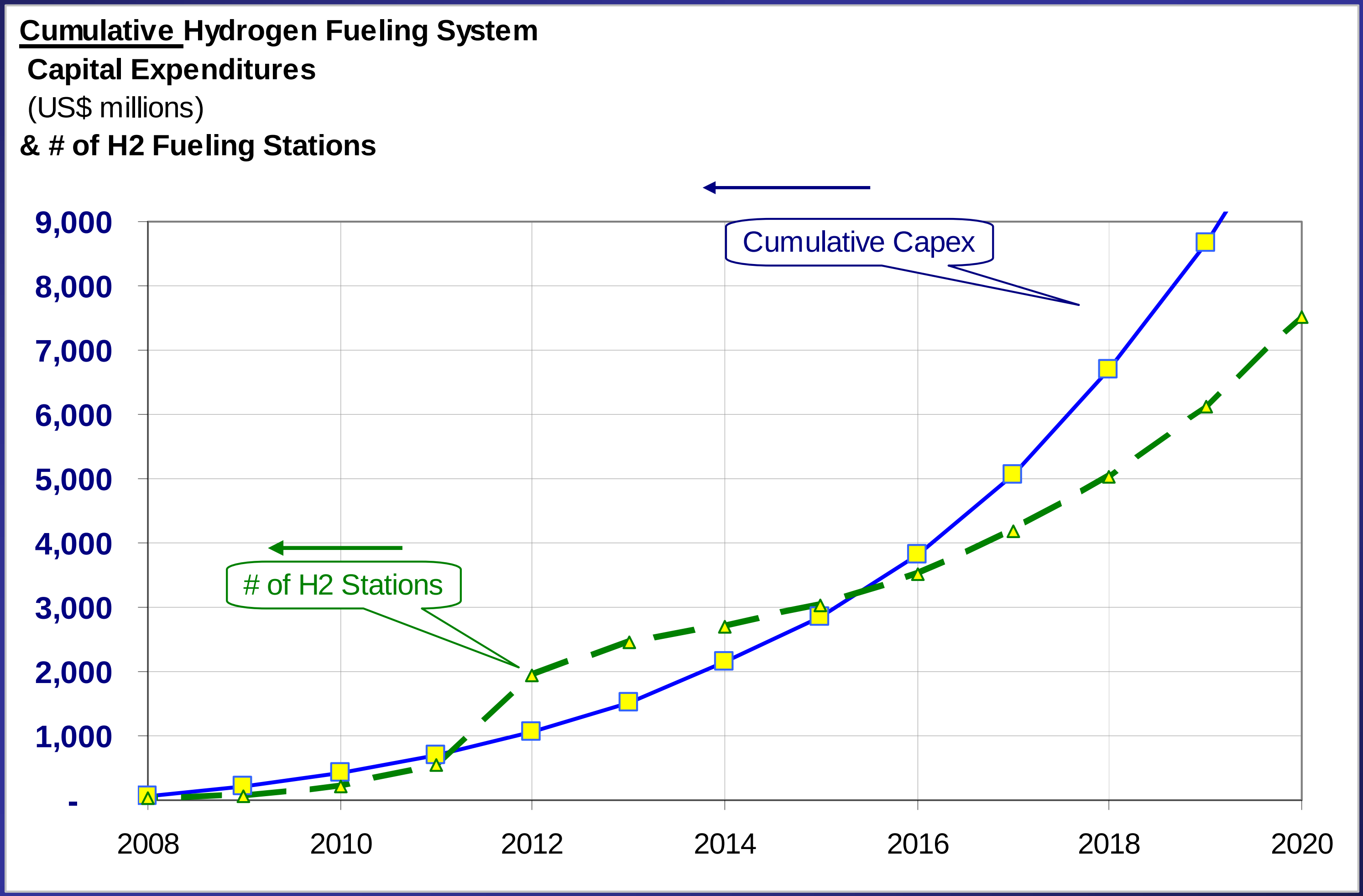
# # of Hydrogen Stations




H2 Energy Story.XLS; Tab 'Annual Sales';CE 23 5/30 /2008

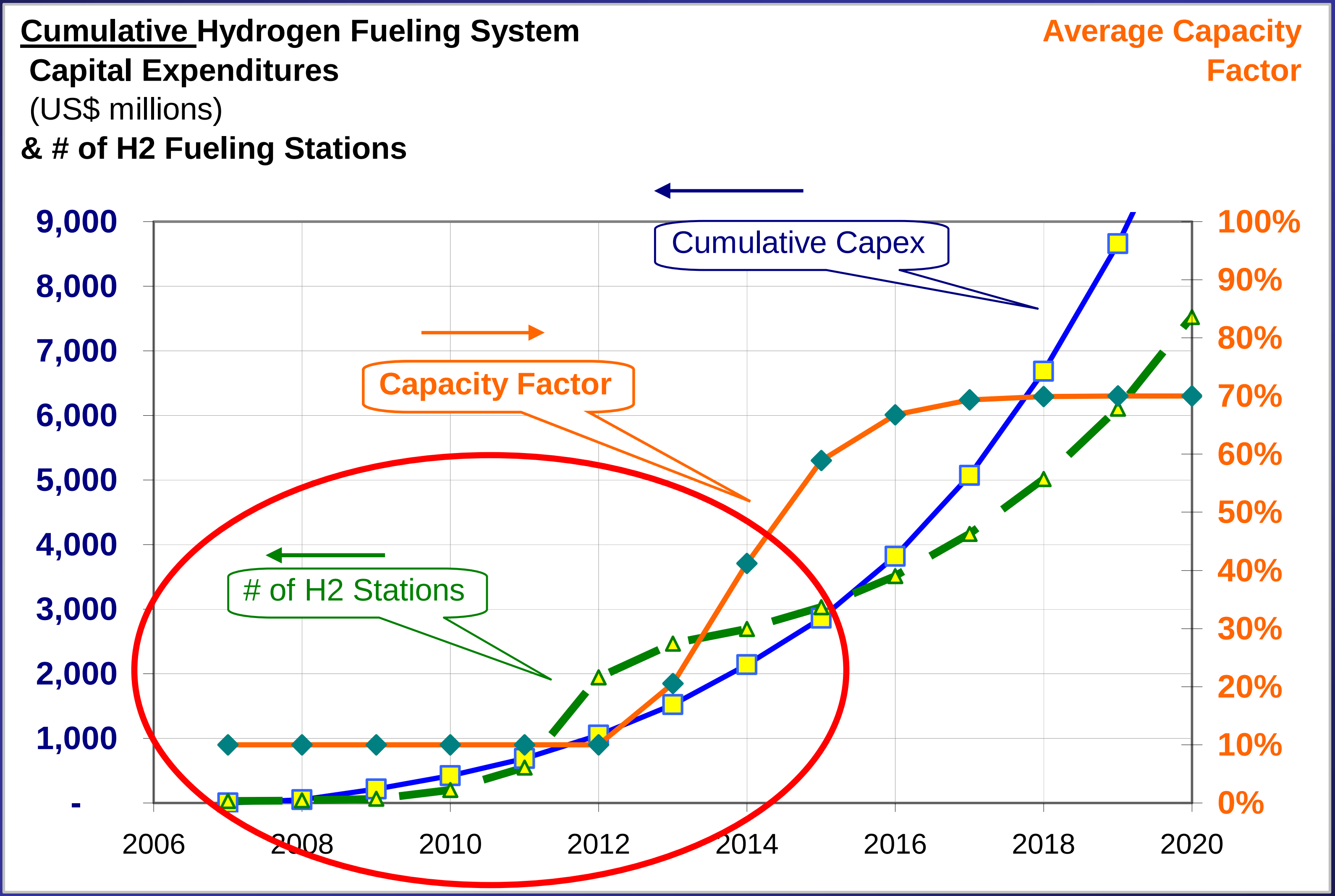
# Cumulative Capital Expenditures on Hydrogen Fueling Equipment

H2Gen



# Initial Hydrogen Fueling System Deployments

H2Gen




H2 Energy Story.XLS; Tab 'Annual Sales';DB 23 5/30 /2008

H2Gen

# HGM 2000:
# Filling 20 cars or 3 busses / day

$$CH_4 + 2H_2O = 4\ H_2 + CO_2$$

**Natural Gas**

**Water**

**Electricity**

**Instrument Air**


Hydrogen,
Up to 99.9999%
pure

All-in life cycle costs today:
Production: $5.35/kg*
[Production, compression & storage: $9.37/kg ($3.95/gge)]

* Natural gas = $11.10/MBTU

# The HGM 3000:
# Filling 30 cars or 4-5 busses / day

All-in life cycle costs today:
Production: $4.33/kg*
[Production, compression & storage: $7.29/kg ($3.08/gge)]

* Natural gas = $11.10/MBTU

# On-site Hydrogen is Competitive with Gasoline

H2Gen

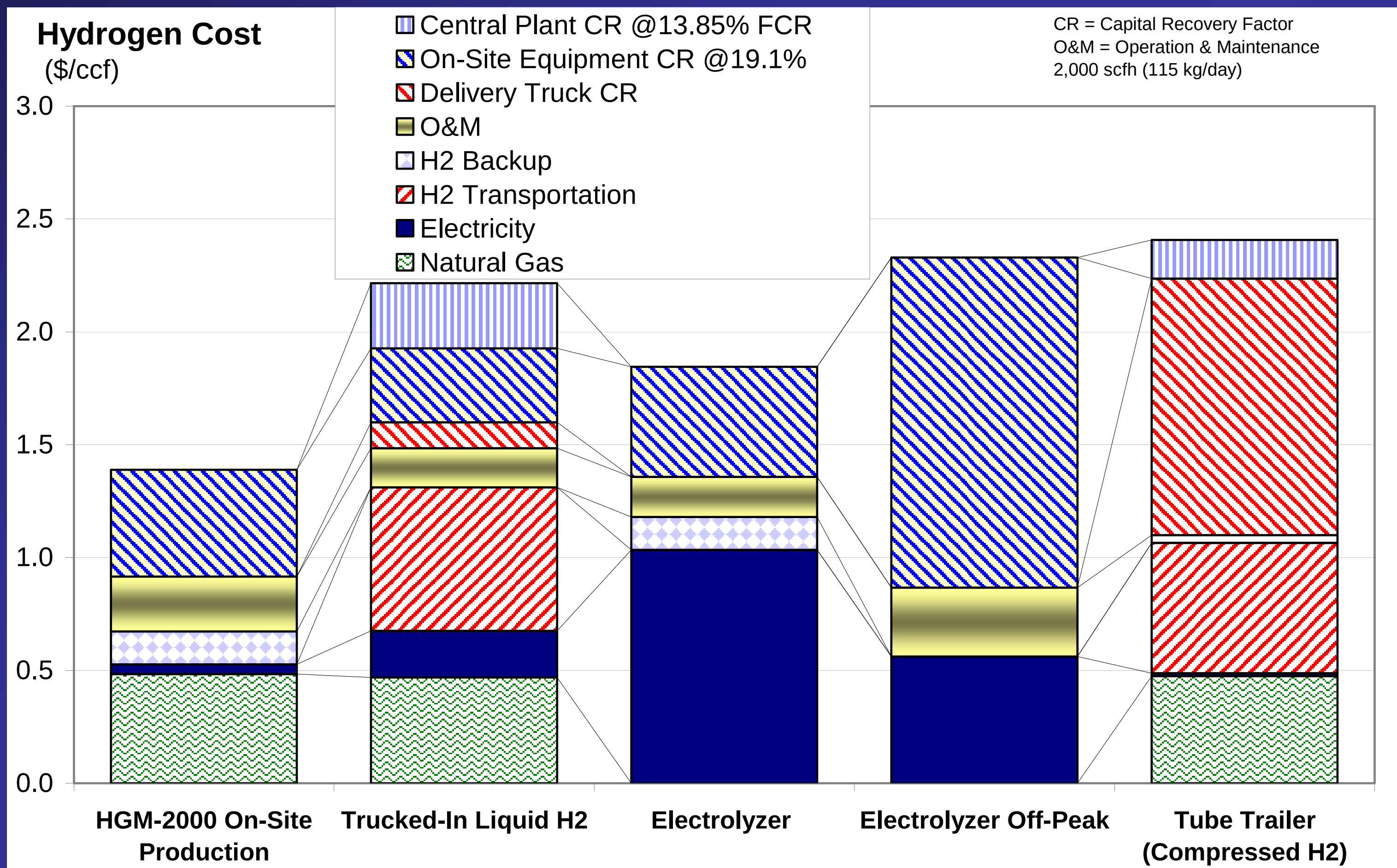
| | | | Hydrogen Cost From On-Site Steam Methane Reformer System ($/kg) | | | **Hydrogen Cost** ($/gallon of gasoline on a range-equivalent basis, untaxed, relative to ICEV) |
|---|---|---|---|---|---|---|
| | Hydrogen Production Capacity | Equipment Production Quantities | Production Cost | Compression & Storage Cost | Total Cost ($/kg) | |
| **HGM2k (20 cars/day)** | **115 kg/day** | **> 10** | 5.95 | 3.42 | 9.37 | **$3.95/gge** |
| **HGM3k (30 cars/day)** | **172 kg/day** | **> 10** | 4.77 | 2.53 | 7.29 | **$3.08/gge** |
| **HGM10k (100 cars/day)** | **575 kg/dy** | **> 10** | 3.80 | 2.10 | 5.91 | **$2.49/gge** |
| **3 Years HGM10k (100 cars/day)** | **576 kg/dy** | **>100** | 3.54 | 1.65 | 5.19 | **$2.19/gge** |
| **~6 Years (250 cars/day)** | **1,500 kg/day** | **>500** | 2.76 | 1.11 | 3.87 | **$1.63/gge** |

NAS Assumptions: Annual Capital Recovery factor = 19.1%; Capacity Factor = 70%; FCV fuel economy = 2.4 X ICEV

Electricity = 8 cents/kWh; Natural Gas = $11.1/MBTU

*H2Gen:Markets4.XLS, Tab'H2 Cost Table' V22;6/6/2008*

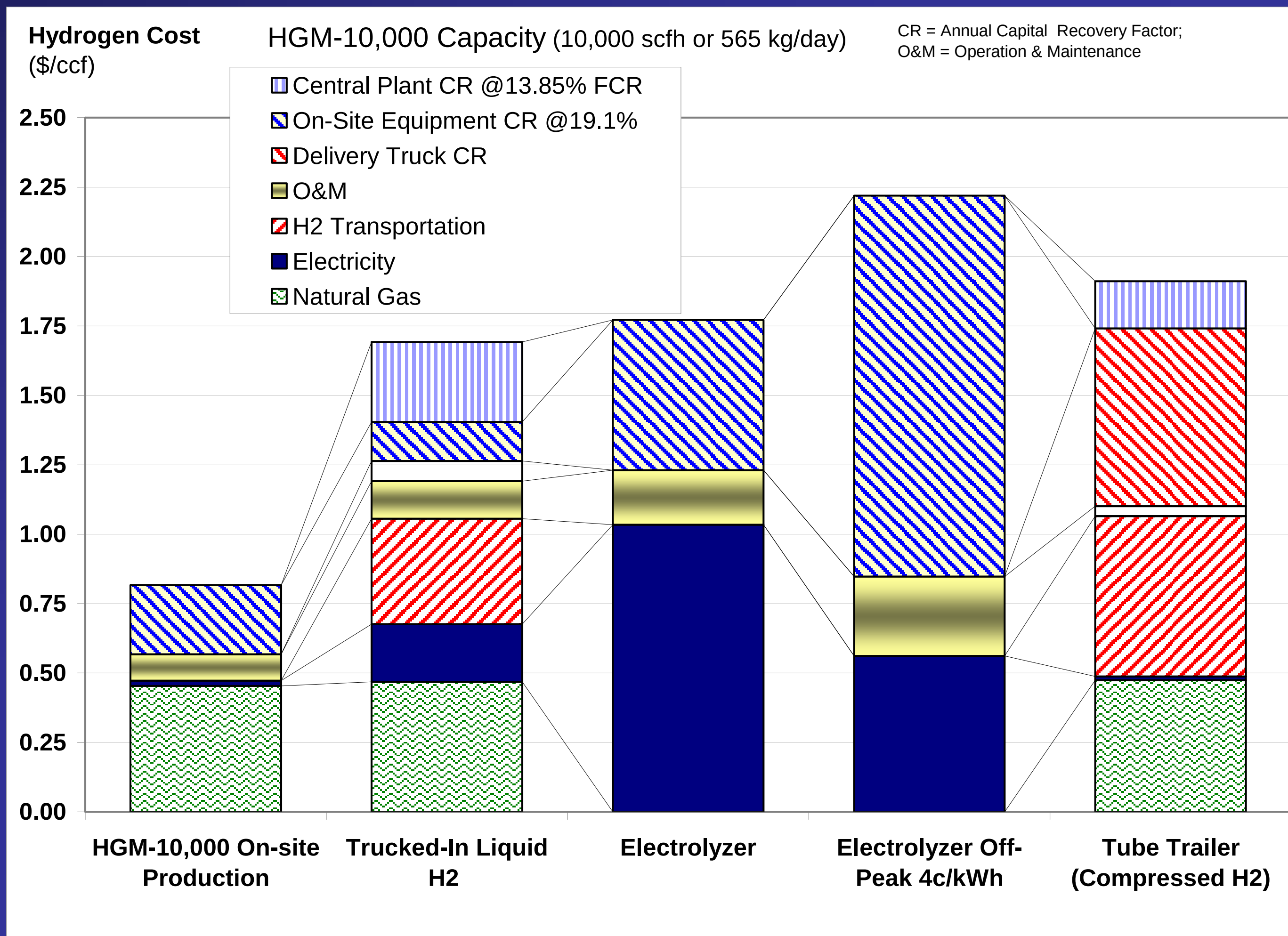
# H2 Cost Comparisons
## (Industrial with HGM-2000)




*H2Gen: markets4.XLS; Tab 'HGM Summary';U183 - 9 / 14 / 2008*

| | On-Site Capital | | Natural gas | Electricity | Distance to Plant | Cap. Recovery |
|---|---|---|---|---|---|---|
| HGM-2000 | $ | 409,643 | $11.10/MBTU | 8.0 cents/kWh | 0 | 19.2% |
| Liquid H2 | $ | 272,924 | $10.00/MBTU | 6.0 cents/kWh | 800 miles | 13.9% |
| Electrolyzer | $ | 415,310 | - | 8.0 cents/kWh | 0 | 19.2% |
| Electrolyzer-Off Peak | $ | 610,230 | - | 4.0 cents/kWh | 0 | 19.2% |
| Tube Trailer | | | $10.00/MBTU | 6.0 cents/kWh | 150 miles | 13.9% |
| Production Quantity | | 10 | Capacity Factor | 95% | | |

# H2 Cost Comparisons
## (Industrial with HGM-10,000)

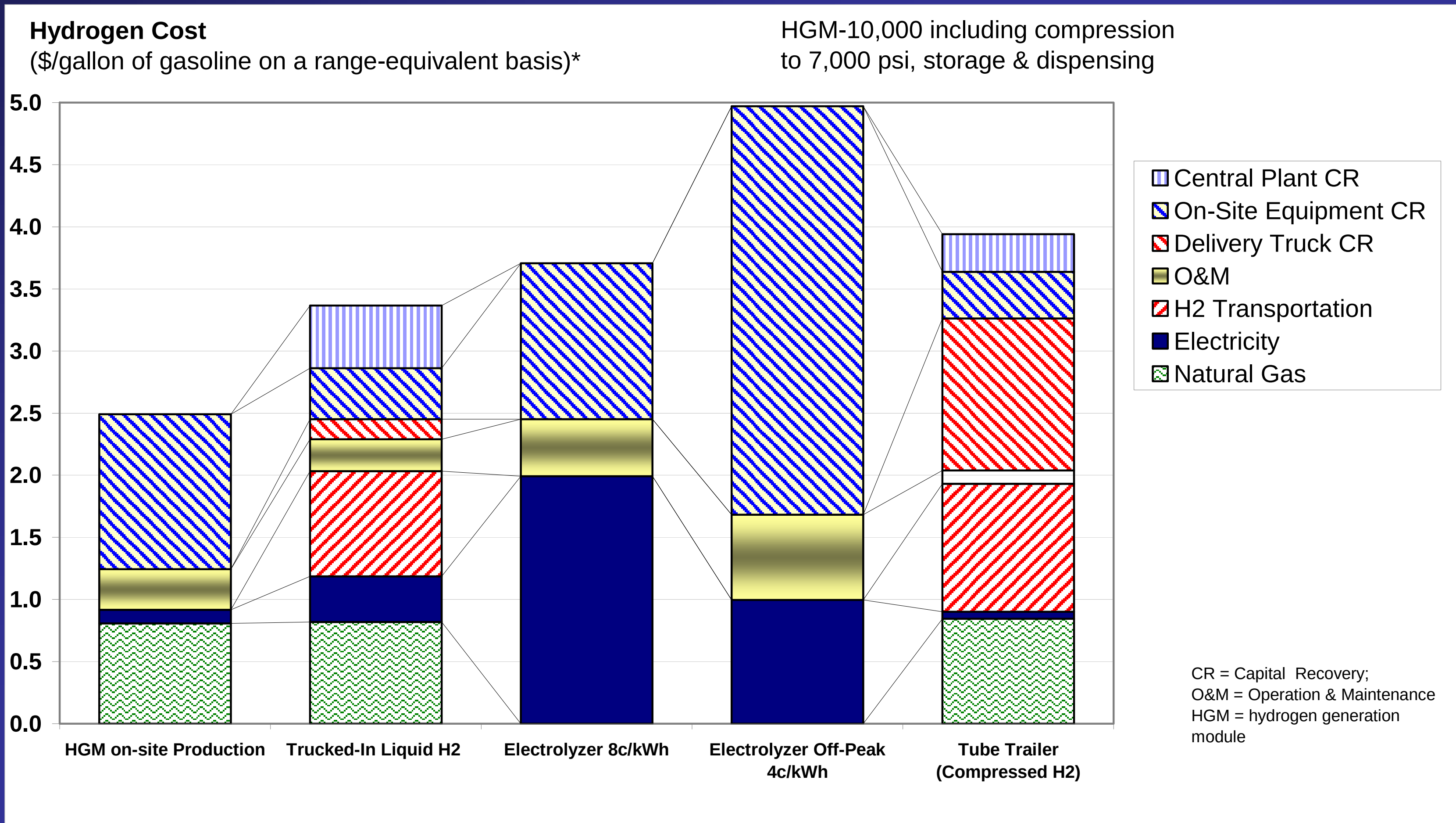



| | On-Site Capital | Natural gas | Electricity | Distance to Plant | Cap. Recovery |
|---|---|---|---|---|---|
| HGM | $ 1,077,019 | $11.10/MBTU | 8.0 cents/kWh | 0 | 19.2% |
| Liquid H2 | $ 582,578 | $10.00/MBTU | 6.0 cents/kWh | 800 miles | 13.9% |
| Electrolyzer | $ 2,298,569 | - | 8.0 cents/kWh | 0 | 19.2% |
| Electrolyzer-Off Peak | $ 2,861,475 | - | 4.0 cents/kWh | 0 | 19.2% |
| Tube Trailer | | $10.00/MBTU | 6.0 cents/kWh | 150 miles | 13.9% |
| Production Quantity | 10 | Capacity Factor | 95% | | |

*H2Gen: markets4.XLS; Tab 'HGM Summary';AE185 - 9 / 14 / 2008*

# H2 Fuel Cost Comparisons

## (Hydrogen fuel including compression, storage & dispensing)




* FCV has 2.4 times higher fuel economy than a comparable ICEV

| | | On-Site Capital | Natural gas | Electricity | Distance to Plant | Cap. Recovery |
|---|---|---|---|---|---|---|
| HGM + CSM + dispenser | $ | 2,229,983 | $11.10/MBTU | 8.0 cents/kWh | 0 | 19.2% |
| Liquid H2 | $ | 716,461 | $10.00/MBTU | 6.0 cents/kWh | 800 miles | 13.9% |
| Electrolyzer | $ | 2,203,575 | - | 8.0 cents/kWh | 0 | 19.2% |
| Electrolyzer-Off Peak | $ | 2,885,660 | - | 4.0 cents/kWh | 0 | 19.2% |
| Tube Trailer | $ | 660,079 | $10.00/MBTU | 6.0 cents/kWh | 150 miles | 13.9% |
| Plant Capacity Factor | | 70% | | | Production Volume | 10 |

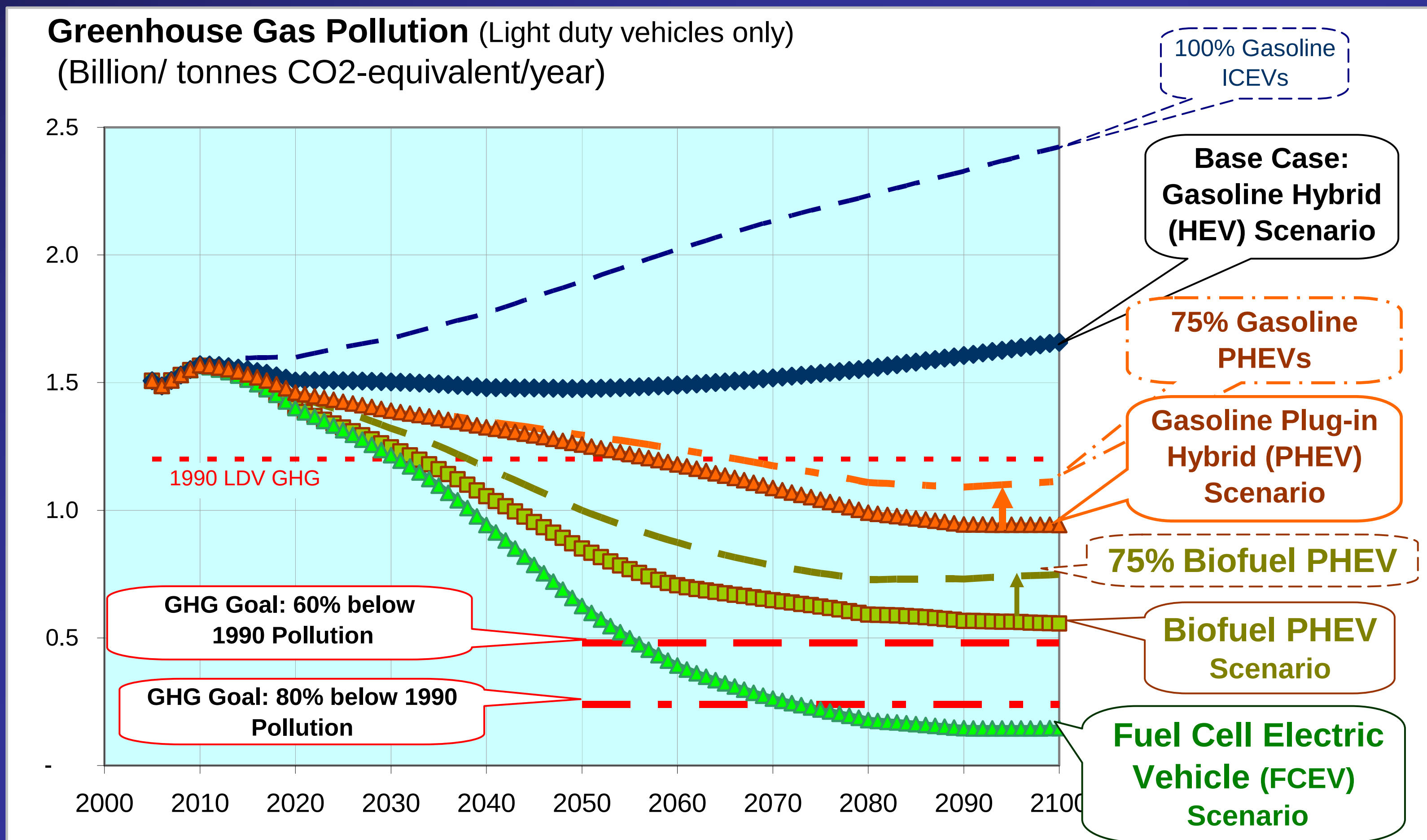
*H2Gen: markets4.XLS; Tab 'HFA Summary'AC250 - 9 / 14 / 2008*

# Acknowledgments


- Joan Ogden (1989 Solar Hydrogen Report)
- Bob Rose, US FC Council (for many helpful comments & guidance over the years)
- UC Davis (Mark Delucchi, et al.)
- US DOE (1994 Ford/DOE/DTI to present; H2A cost model, Steve Chalk, JoAnn Milliken, et al.)
- Argonne National Lab (Michael Wang & GREET model)
- NHA hydrogen story task force (Frank Novachek, leader, John Elter – Stationary applications)
- Barney Rush (CEO $H_2$Gen)

# GHG: 75% Cap on PHEVs

## (Due to limited night-time access to outlets)

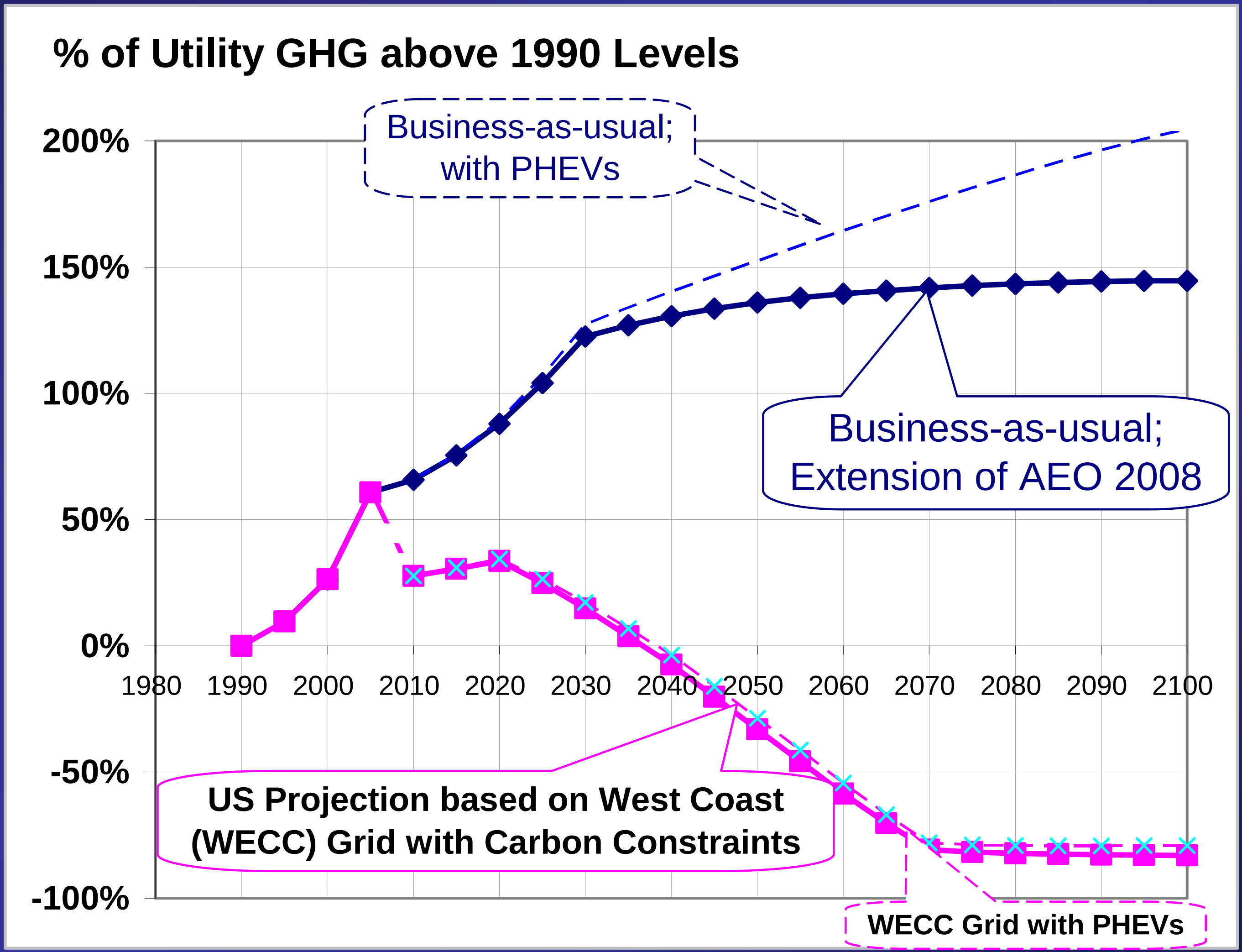



Story Simultaneous.XLS; Tab 'Graphs'; Q 494 3/4 /2009



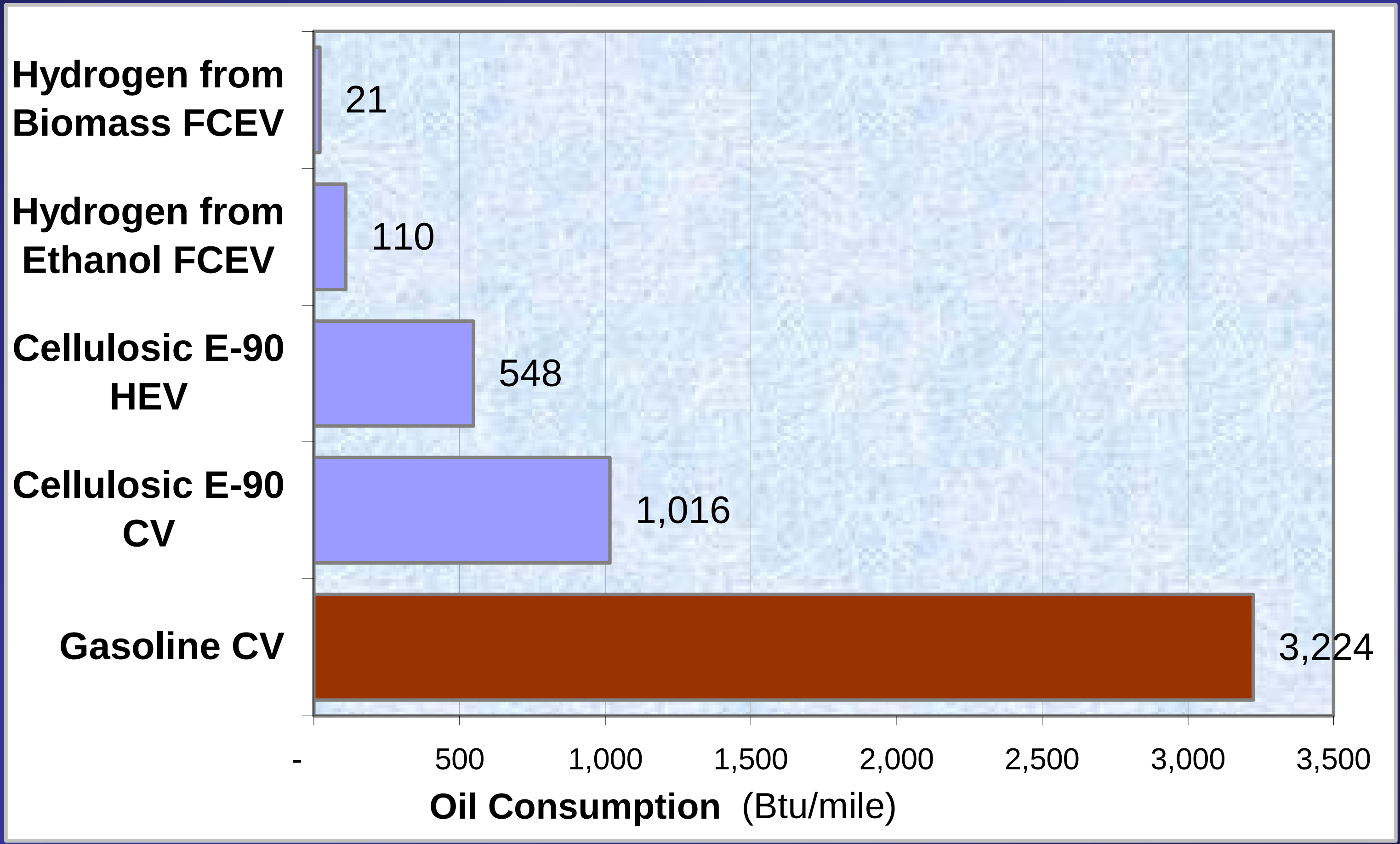
Sources: Argonne National Laboratory GREET 1.8a, AEO 2009 & NHA models

# Grid GHGs Relative to 1990



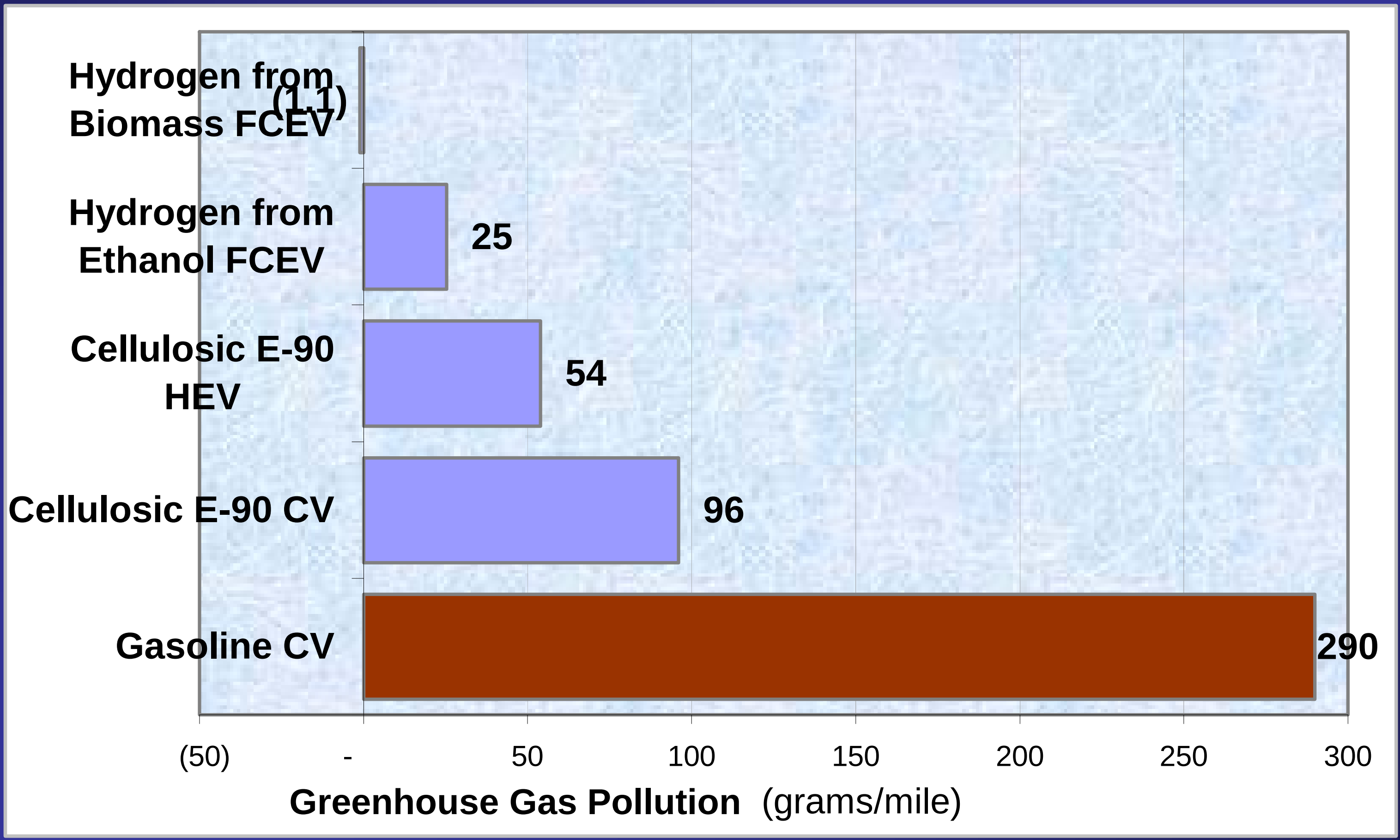

GHG.XLS, Tab 'Climate Change Projections'; K422;5/13/2009

# Hydrogen from Ethanol & Biomass: Oil Consumption Comparison



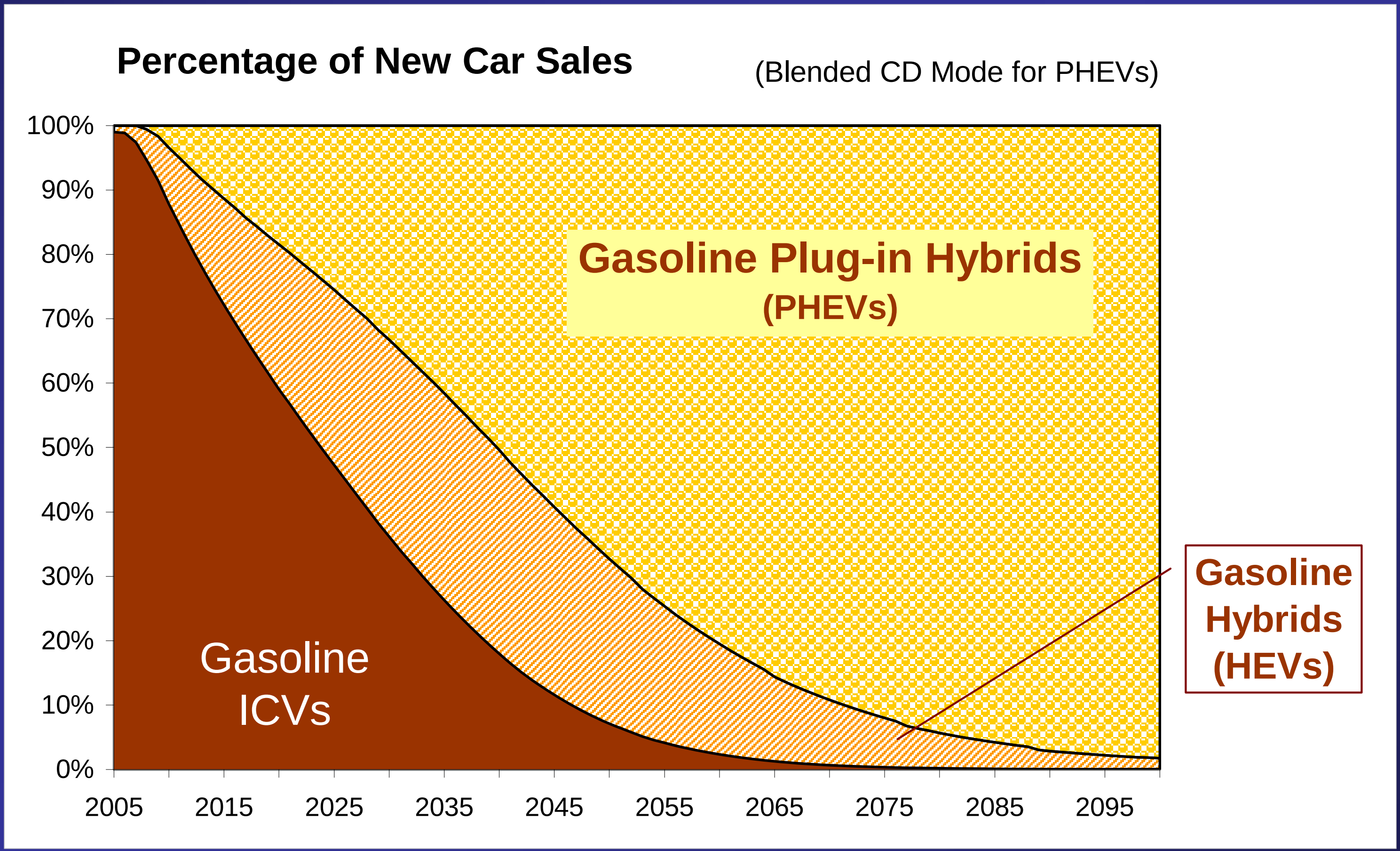

Hydrogen Production Efficiency.XLS; Tab 'GREET'; J 53 3/6 /2009

# Hydrogen from Ethanol & Biomass: Greenhouse Gas Comparisons




Hydrogen Production Efficiency.XLS; Tab 'GREET'; J 74 3/6 /2009

# 100% Gasoline Plug-In ICE Hybrid Electric Vehicle (PHEV) Scenario Market Shares

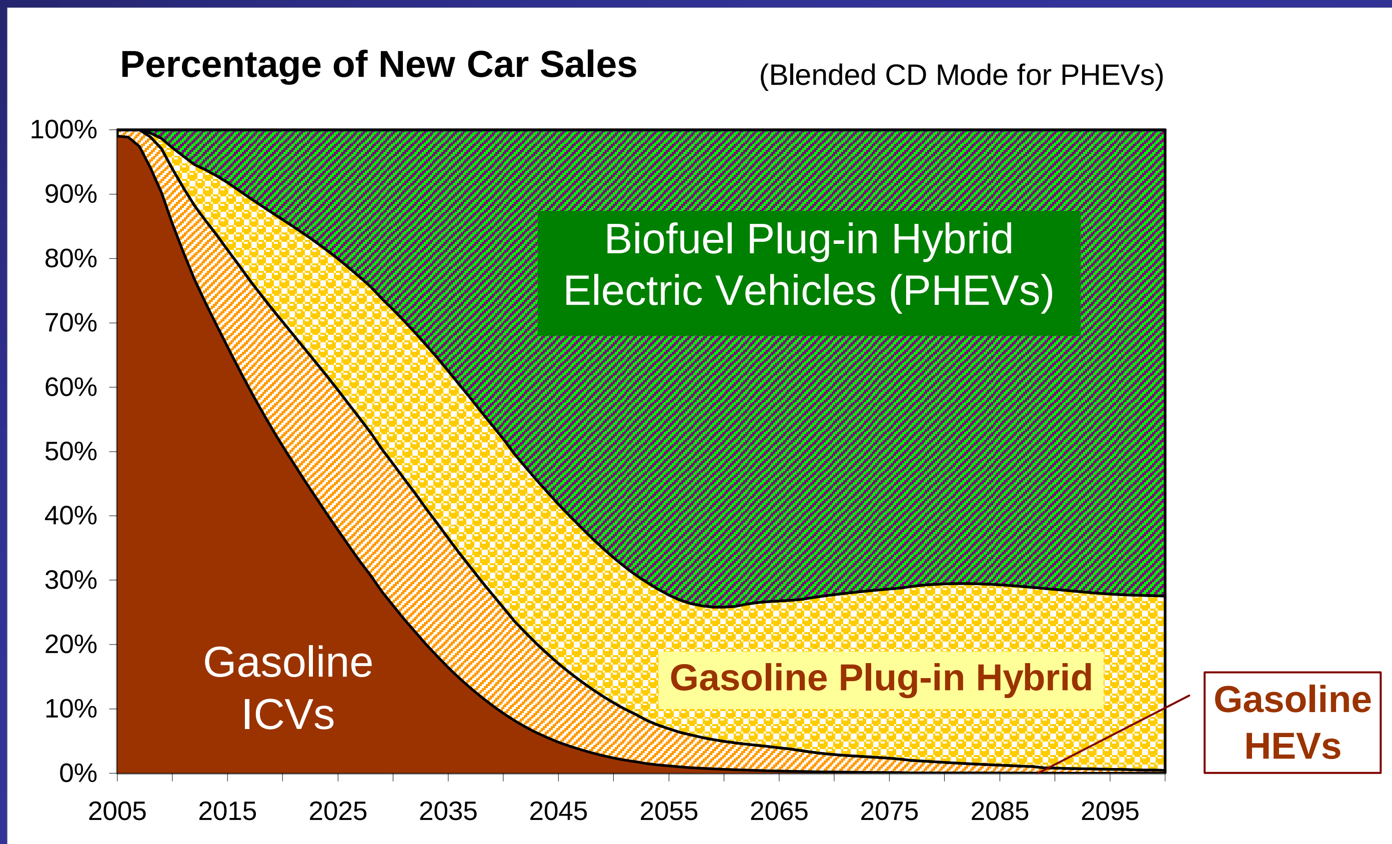



Story Simultaneous.XLS; Tab 'Graphs'; ED 30 3/1 /2009

(50% market share potential by 2031; 75% limit to night-time charging; 12 to 52 mile all-electric range; 18% to 65% of VMT from grid)

# Biofuel Plug-In Hybrid Scenario Market Shares

## (90 Billion gallons/year of biofuels)




Story Simultaneous.XLS; Tab 'Graphs'; ED 30 3/4 /2009

[50% market share potential by 2031, no limit on night-time charging outlets; 90 billion gallon/year cellulosic ethanol production per Sandia/Livermore (vs. 8 B/yr now and 60 B gallon/yr limit used by NRC)]

# Alternative Vehicle/Fuel Combinations

| | ICEV | ICE HEV | ICE PHEV | FC HEV | FC PHEV | BEV |
|---|---|---|---|---|---|---|
| Fuel Economy | 1.0 | 1.39 | 1.39 | 2.45 | 2.45 | |
| Gasoline | Ref | X | X | | | |
| Natural Gas | X | X | X | | | |
| Diesel | | X | X | | | |
| Ethanol | X | X | X | | | |
| Hydrogen | | X | X | X | X | |
| Electricity | | | S | | S | X |

X = primary fuel; S = secondary fuel; ICEV = internal combustion engine vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; FC = fuel cell; BEV = battery-powered electric vehicle

# Four Main Vehicle/Fuel Combinations

| | ICEV | ICE HEV | ICE PHEV | FC HEV | FC PHEV | BEV |
|---|---|---|---|---|---|---|
| Fuel Economy | 1.0 | 1.39 | 1.39 | 2.45 | 2.45 | |
| Gasoline | Ref | X | X | | | |
| Natural Gas | X | X | X | | | |
| Diesel | | X | X | | | |
| Ethanol | X | X | X | | | |
| Hydrogen | | X | X | X | X | |
| Electricity | | | S | | S | X |

X = primary fuel; S = secondary fuel; ICEV = internal combustion engine vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; FC = fuel cell; BEV = battery-powered electric vehicle

# Two Reference Vehicle/Fuel Combinations

| | ICEV | ICE HEV | ICE PHEV | FC HEV | FC PHEV | BEV |
|---|---|---|---|---|---|---|
| Fuel Economy | 1.0 | 1.39 | 1.39 | 2.45 | 2.45 | |
| Gasoline | Ref | X | X | | | |
| Natural Gas | X | X | X | | | |
| Diesel | | X | X | | | |
| Ethanol | X | X | X | | | |
| Hydrogen | | X | X | X | X | |
| Electricity | | | S | | S | X |

X = primary fuel; S = secondary fuel; ICEV = internal combustion engine vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; FC = fuel cell; BEV = battery-powered electric vehicle

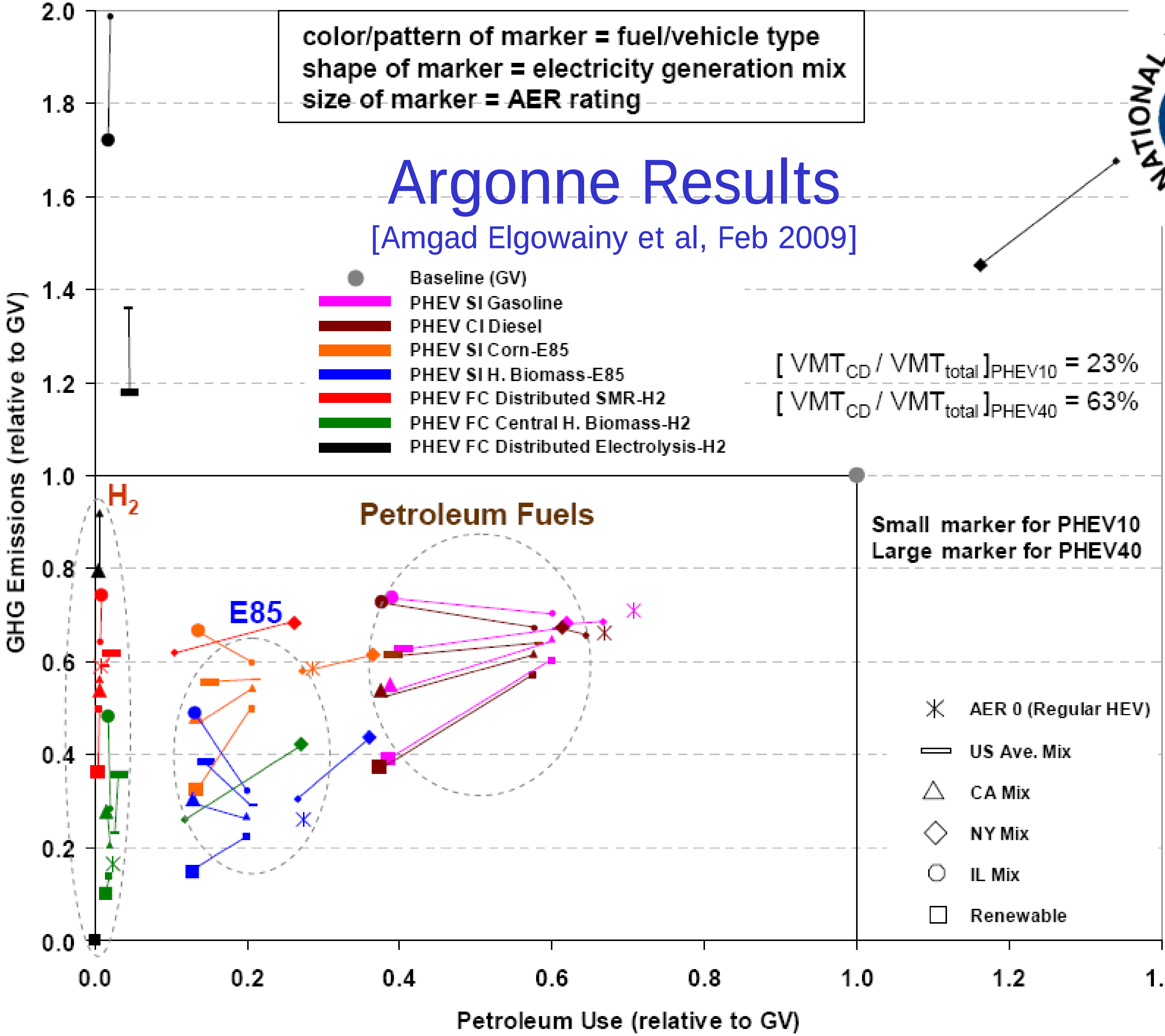
# Alternative Vehicle/Fuel Combinations

| | ICEV | ICE HEV | ICE PHEV | FC HEV | FC PHEV | BEV |
|---|---|---|---|---|---|---|
| Fuel Economy | 1.0 | 1.39 | 1.39 | 2.45 | 2.45 | |
| Gasoline | Ref | X | X | | | |
| Natural Gas | X | X | X | | | |
| Diesel | | X | X | | | |
| Ethanol | X | X | X | | | |
| Hydrogen | | X | X | X | X | |
| Electricity | | | S | | S | X |

X = primary fuel; S = secondary fuel; ICEV = internal combustion engine vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; FC = fuel cell; BEV = battery-powered electric vehicle

# Argonne Results

[Amgad Elgowainy et al, Feb 2009]



# National Hydrogen Association

## Alternative Vehicle Simulation Study Objectives:

- Compare alternative vehicles & fuels over 100 years with respect to:
  - Oil consumption
  - Greenhouse gas emissions
  - Urban air pollution
- Estimate cost of hydrogen infrastructure and fuel cell vehicle incentives

H2Gen

# Framing the Issue

*Not* PHEVs vs. FCEVs…

…*but* ICE-PHEVs vs. Fuel Cell HEVs or Fuel Cell PHEVs

# Current # of On-Road Vehicles made by auto companies

- ICE-PHEVs: 1
- FC-PHEVs: 1
- FC-HEVs: 318*

Toyota ICE Plug-in Hybrid Electric Vehicle (7 miles AER)

Ford Fuel Cell Plug-in Hybrid Electric Vehicle

(25 miles AER)

*140 FC HEVs under DOE learning demonstration evaluation program have logged over 1.9 million miles with over 16,000 refuelings in last four years with an average fueling time of 3.3 minutes (Ref: Wipke, NREL)

# Which vehicles are best for society?

- ICE hybrid electric vehicles?
- ICE plug-in hybrids?
- Fuel cell hybrid electric vehicles?
- Fuel cell plug-in hybrids?

*…….or all of the above!*