

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

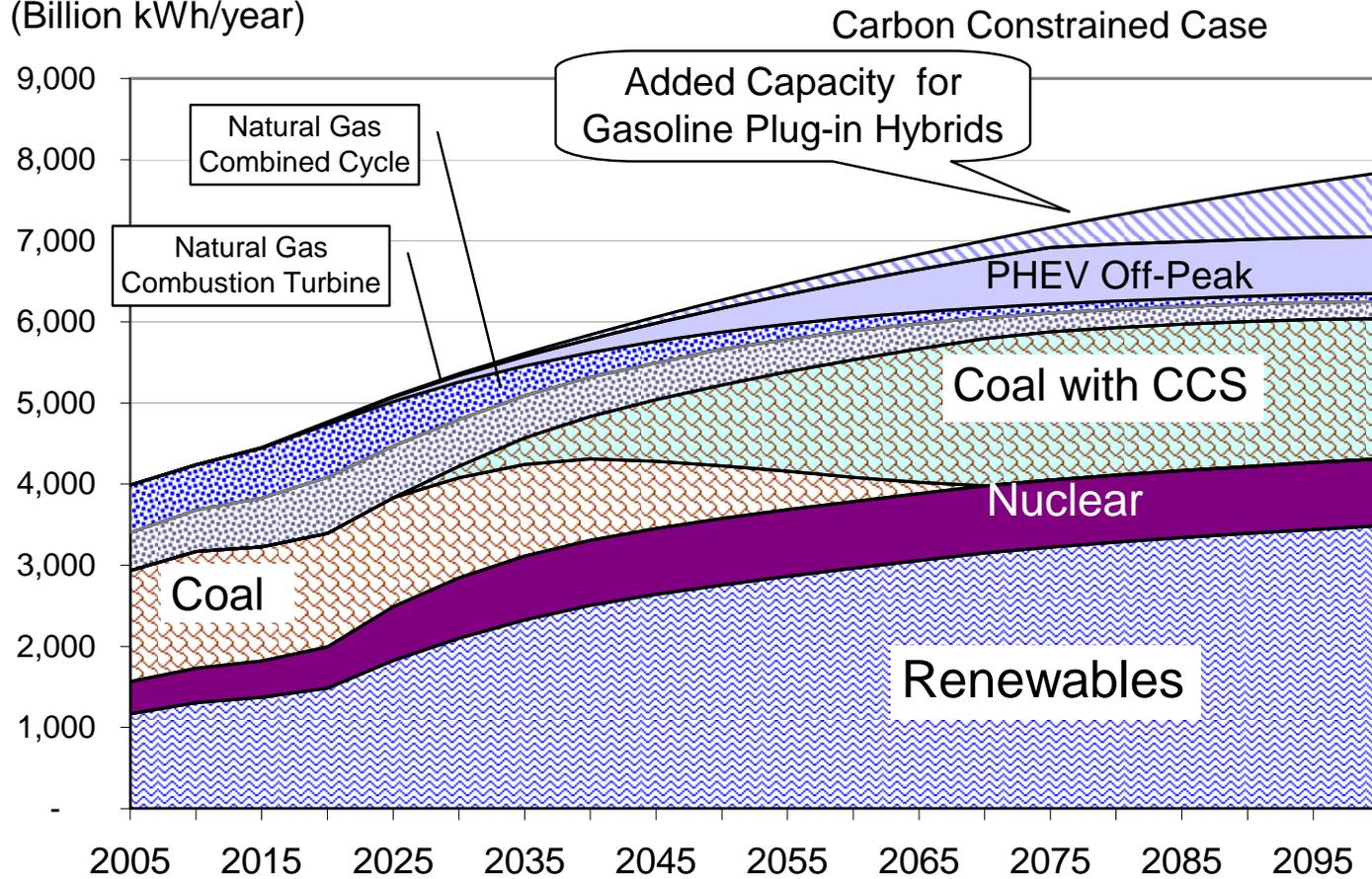


- Assume success for all options
 - Technical success
 - Vehicles are affordable
- Assume stringent climate change constraints
 - Hydrogen production becomes green over time
 - Electricity production becomes green over time

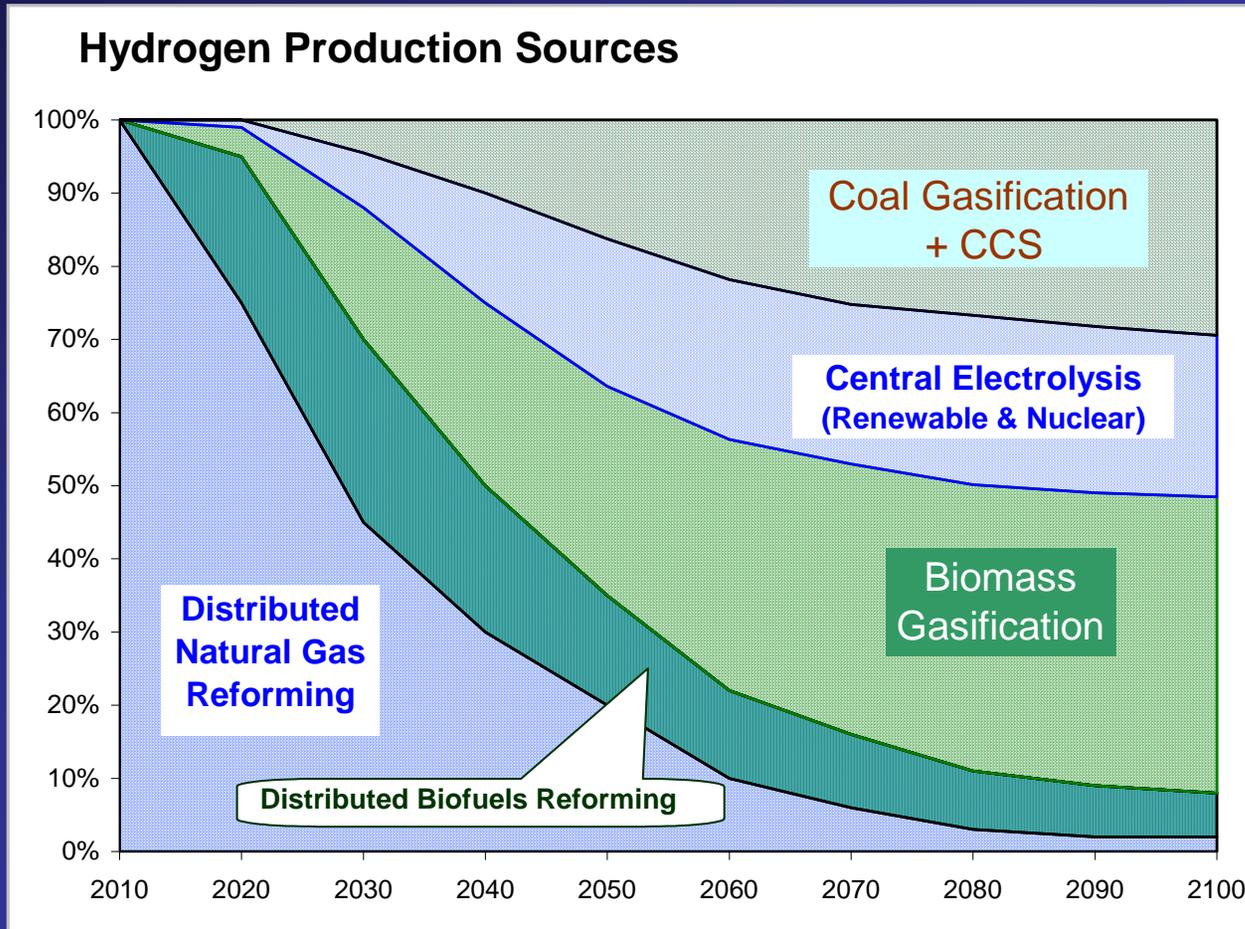
Greening of Electrical Grid



West Coast (WECC) Electricity Consumption Scaled to US
(Billion kWh/year)



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)

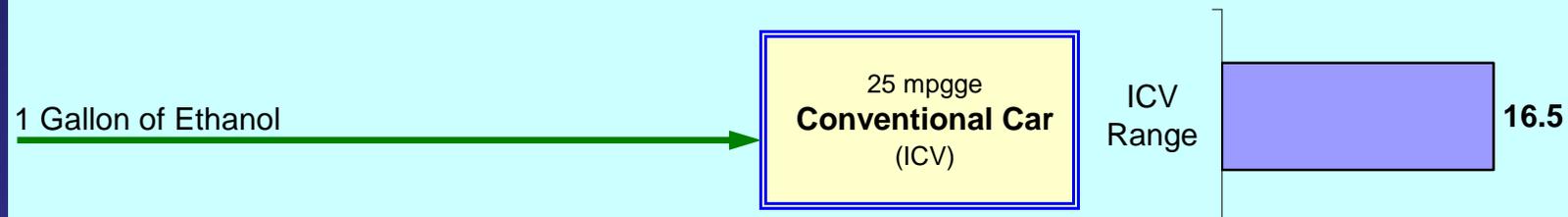
Summary_Greet 1.8a.XLS; Tab 'Fuel TS'; N.97; 3/1/2009

	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%



Why Hydrogen from Ethanol?

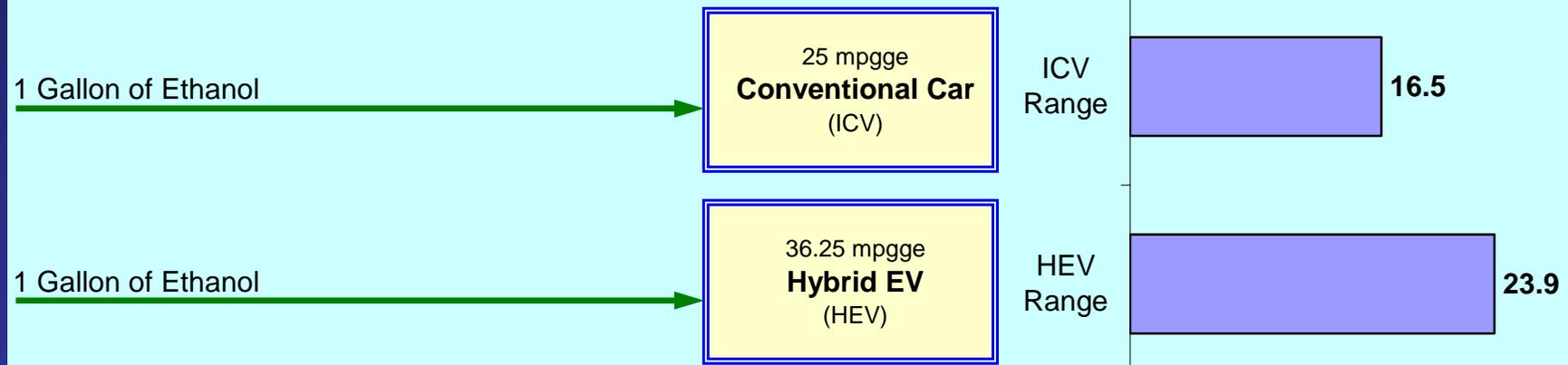
ICV fuel economy	25 mpgge
HEV mpg/ ICV mpg	1.45
FCEV mpg/ ICV mpg	2.4
SMR HHV Efficiency	76%





Why Hydrogen from Ethanol?

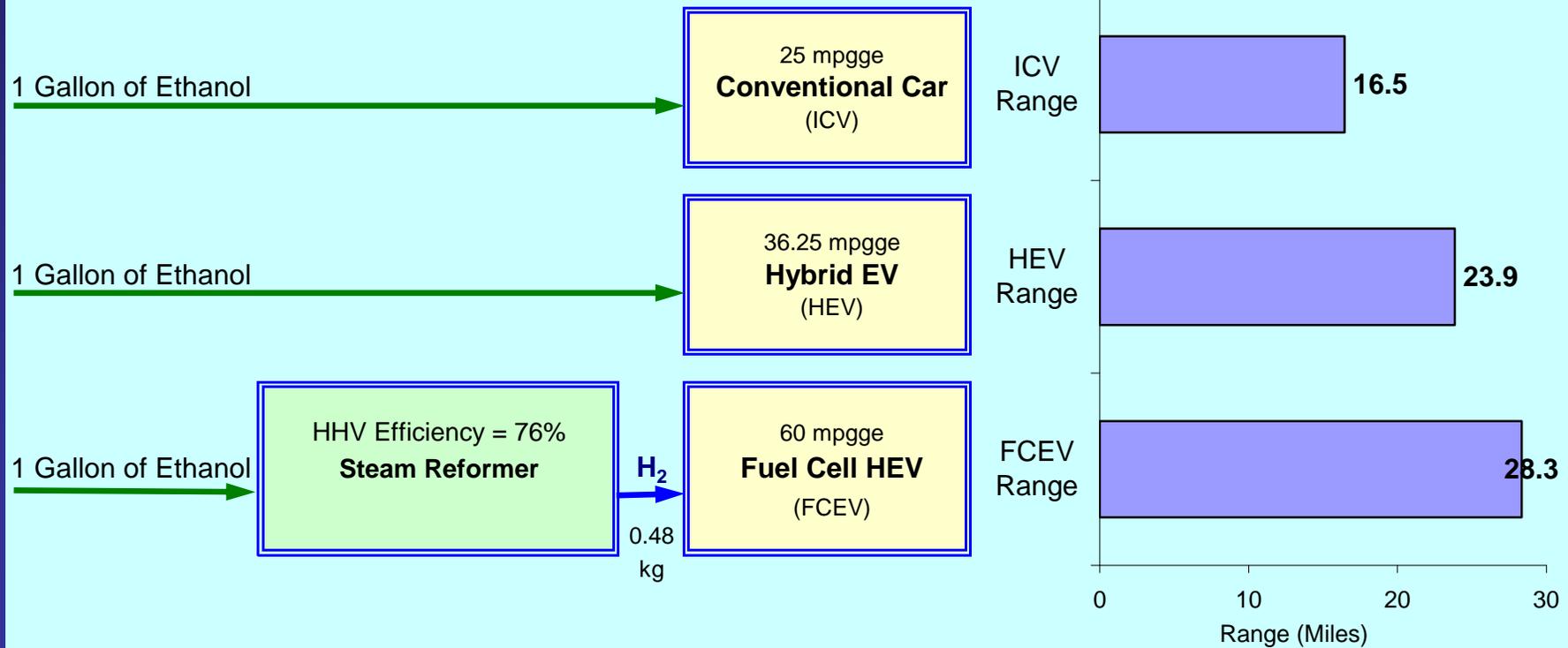
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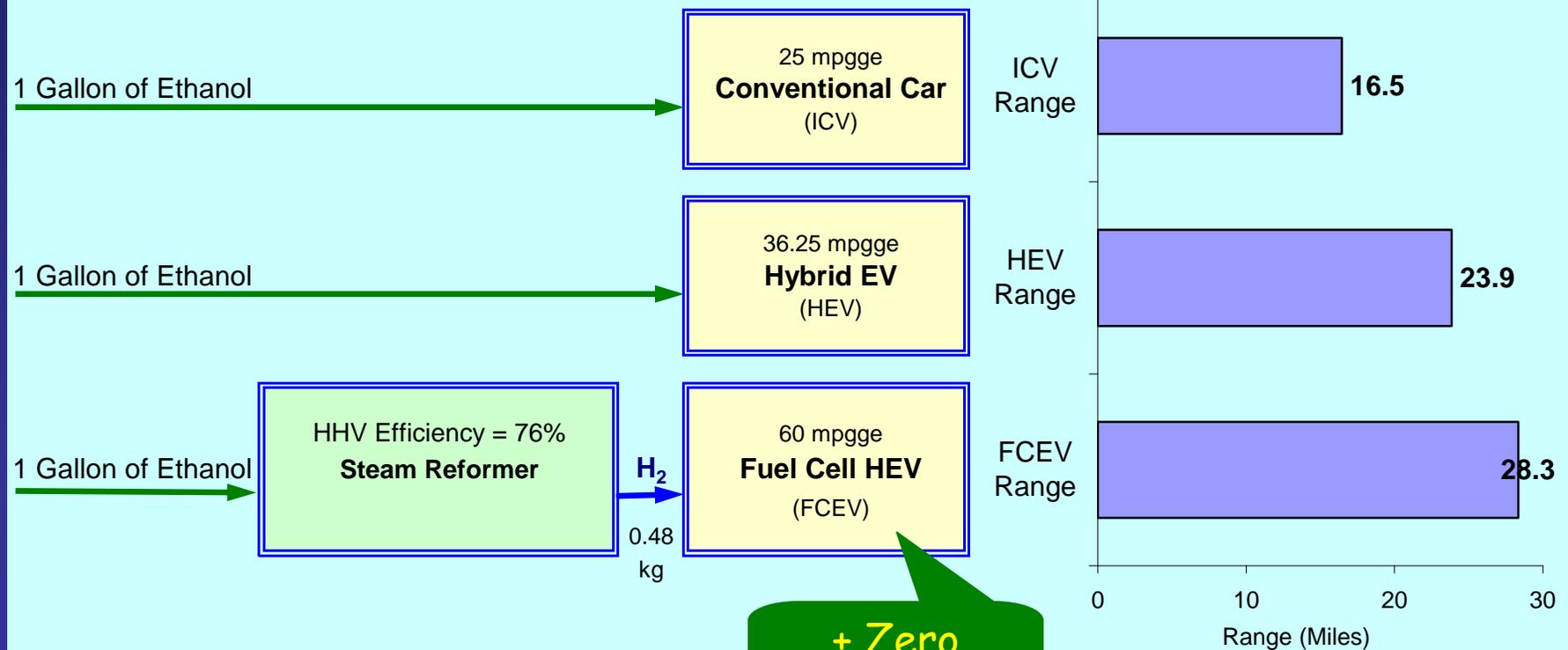




Why Hydrogen from Ethanol?

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

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

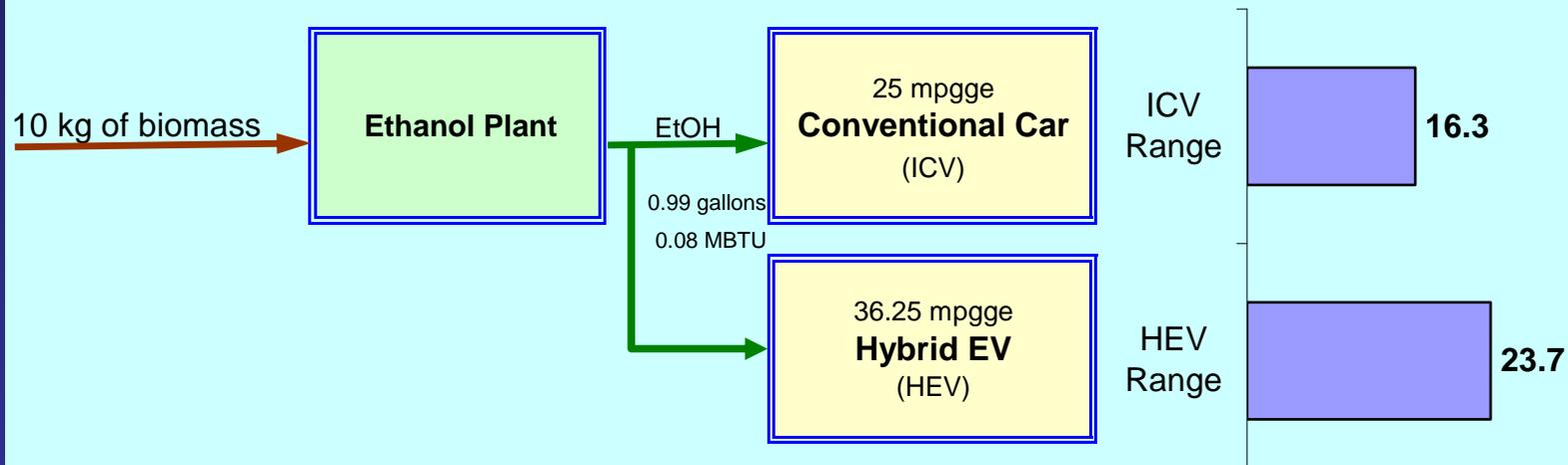


+ Zero Emissions

Consider Biomass Feedstock



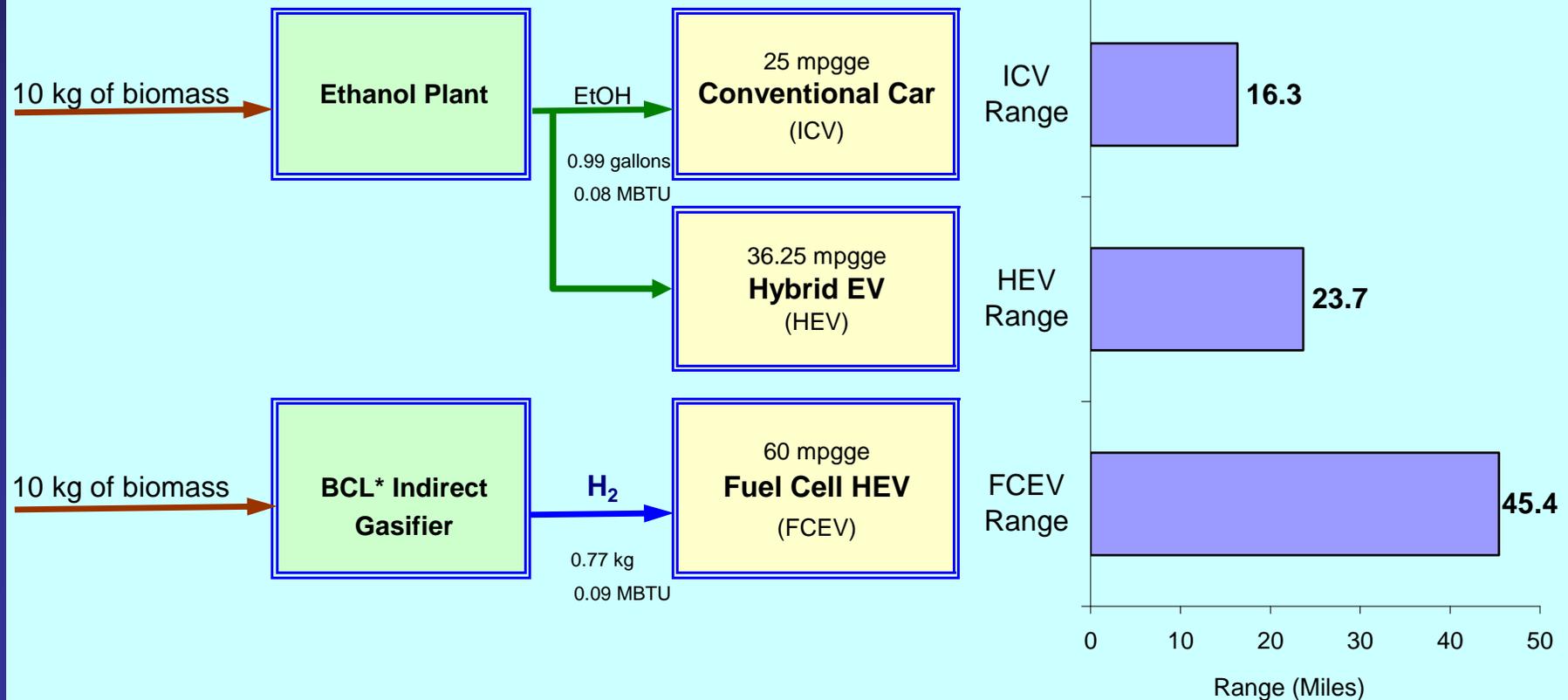
ICV fuel economy	25 mpgge
HEV mpg/ ICV mpg	1.45
FCEV mpg/ ICV mpg	2.4
Biomass Gasifier LHV Efficiency	49%
Ethanol Plant Productivity	90 gal EtOH/ton biomass





Better yet: Biomass Gasification

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



BCL* = Battelle Columbus Laboratory

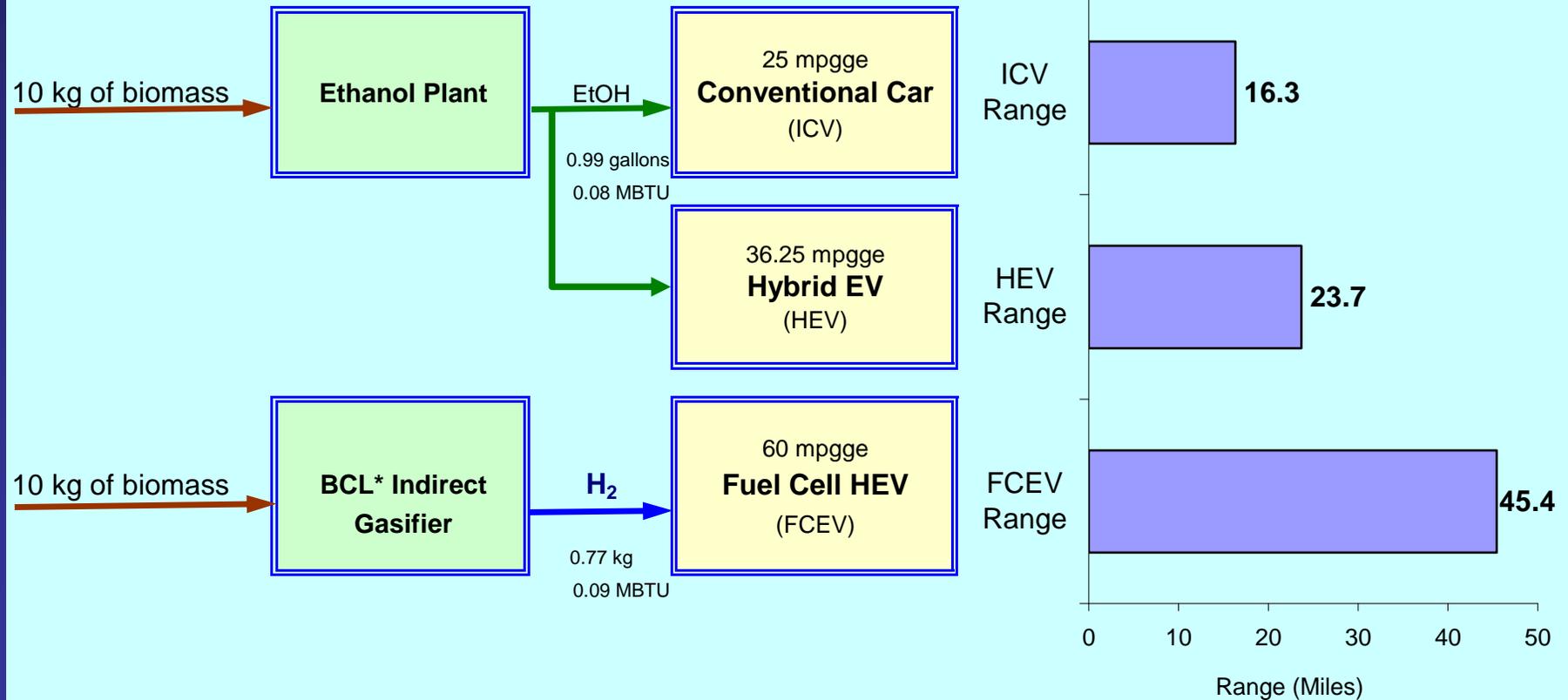
Why hydrogen from ethanol.XLS; Tab 'Chart Biomass'; Q 32 2/24/2009



Biomass Gasification

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

FCEV Range Increase Factors	
w/r to ICV:	2.8
w/r to HEV	1.9





What fuels?

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

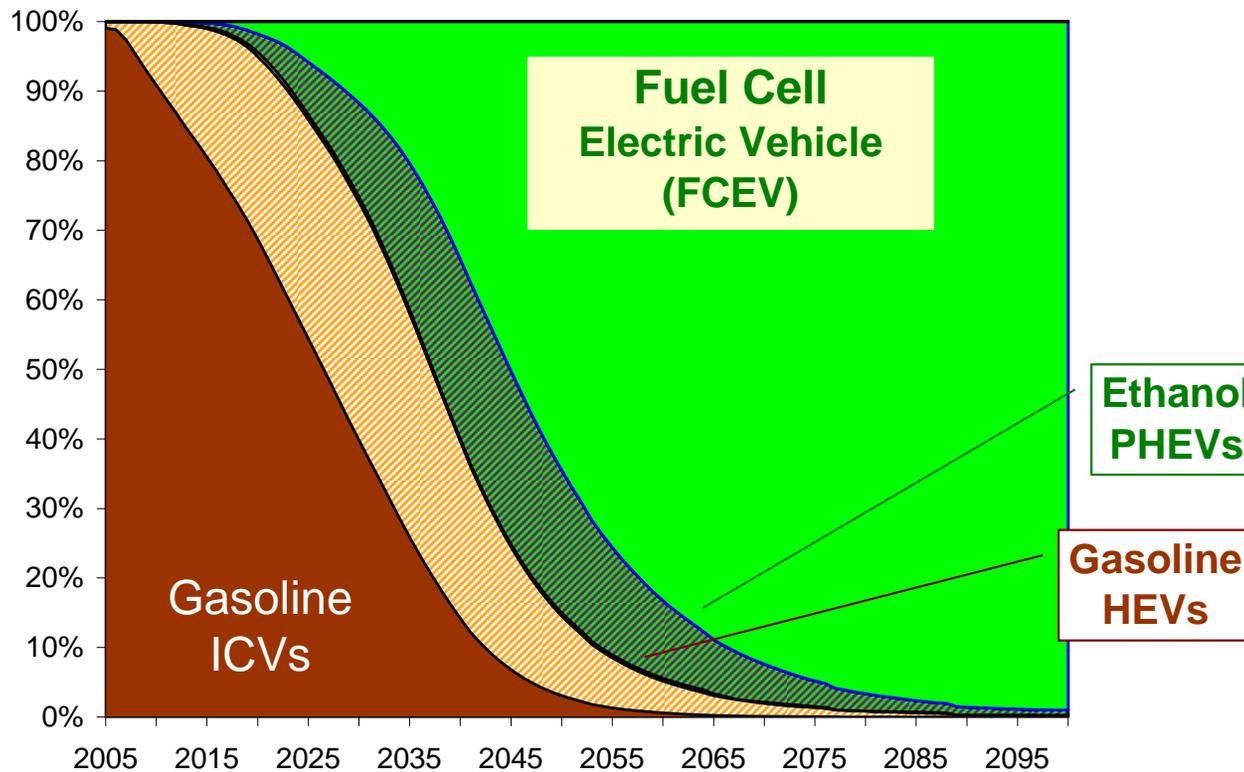
** FCEV includes peak power augmentation with batteries or ultracapacitors*

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



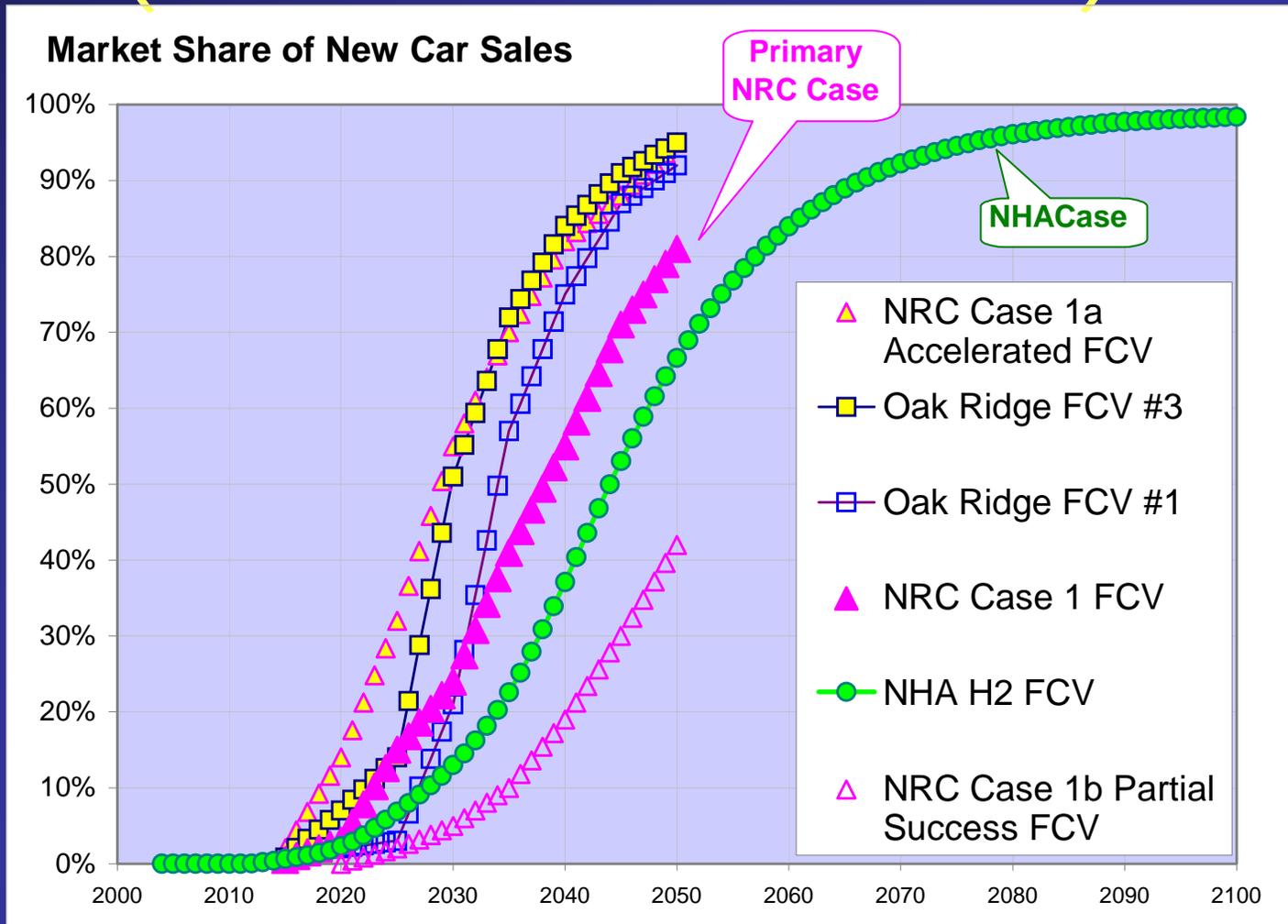
Percentage of New Car Sales

(Blended CD Mode for PHEVs)

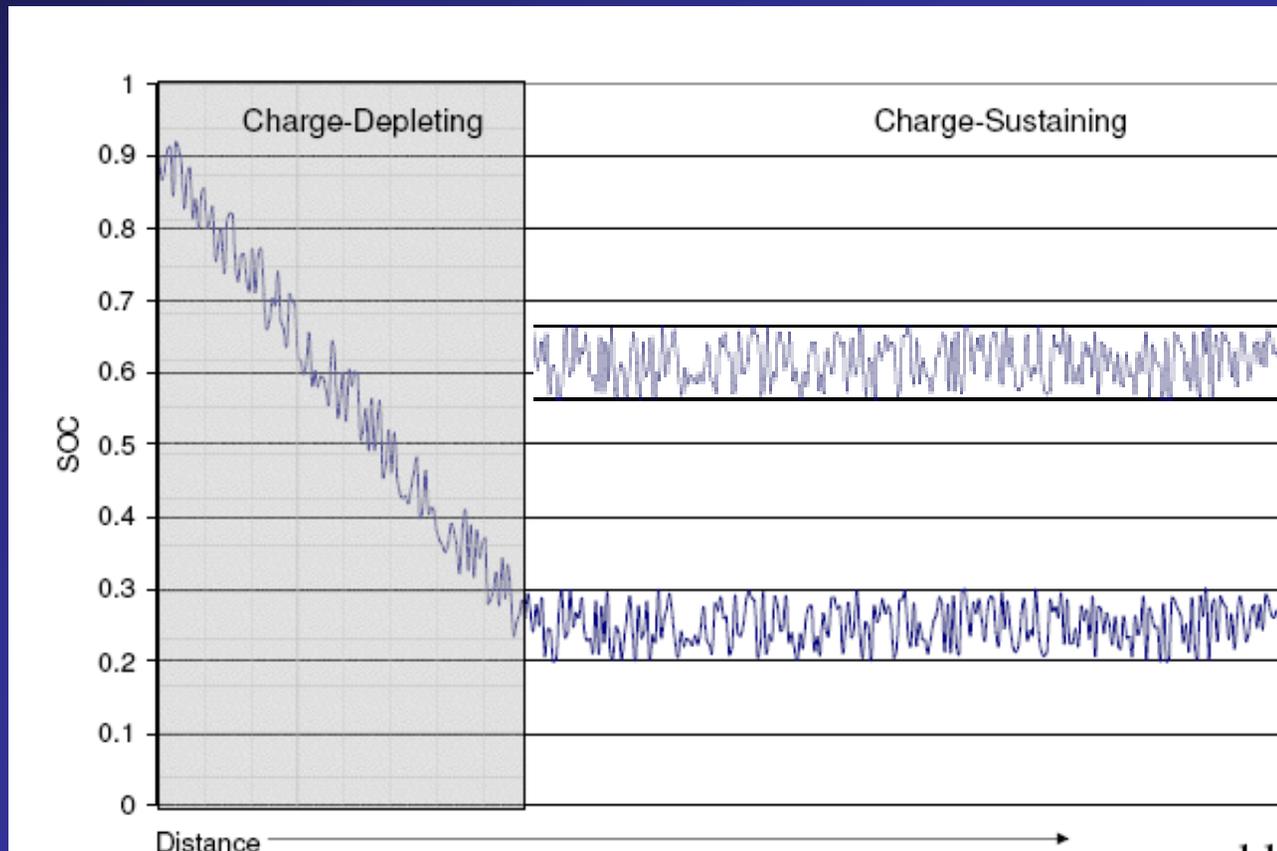


(50% Market Share Potential by 2035)

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



PHEV Charging Modes



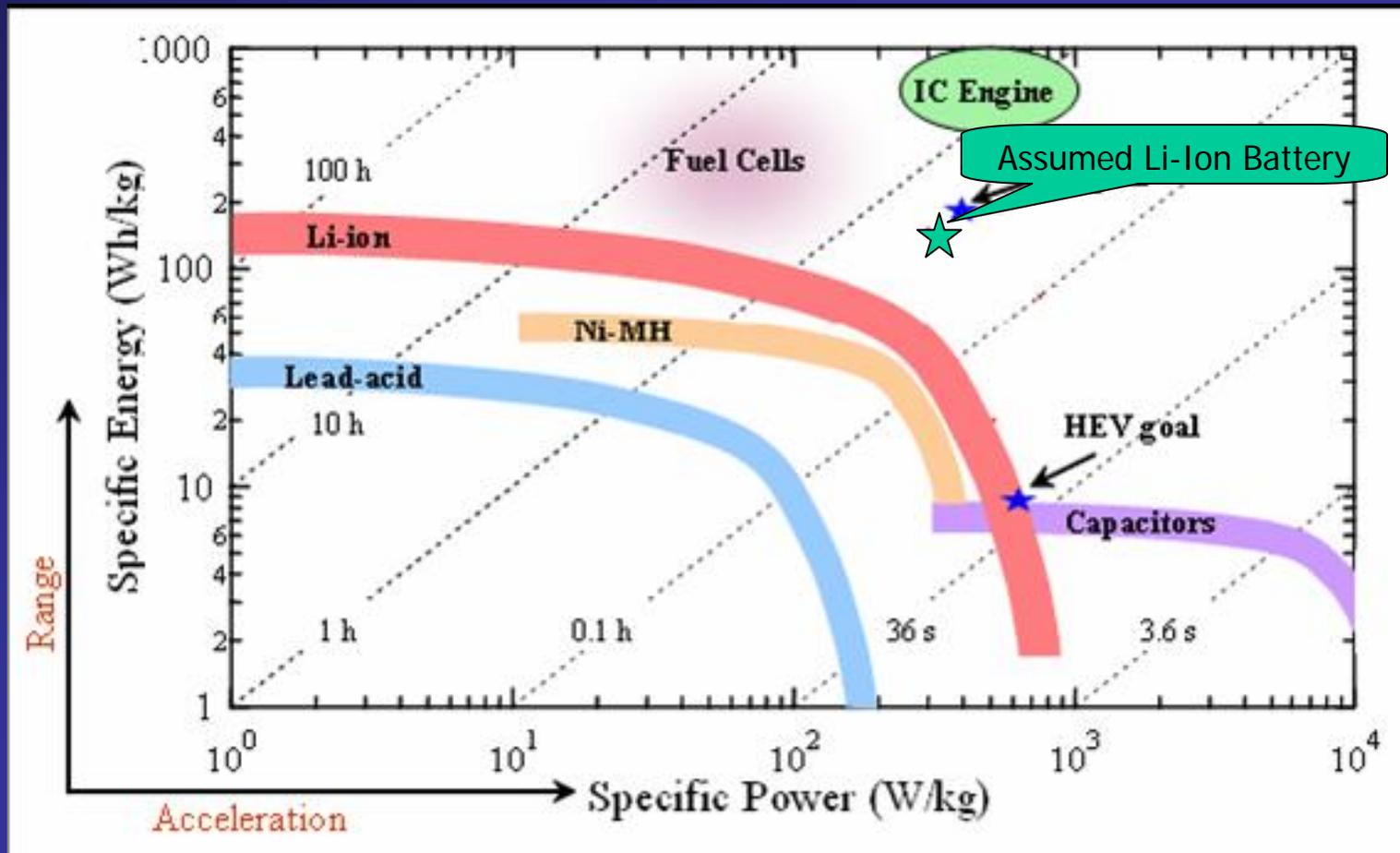
[Ref: Kromer
& Heywood,
MIT]

Blended Charge-Depleting Mode:

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



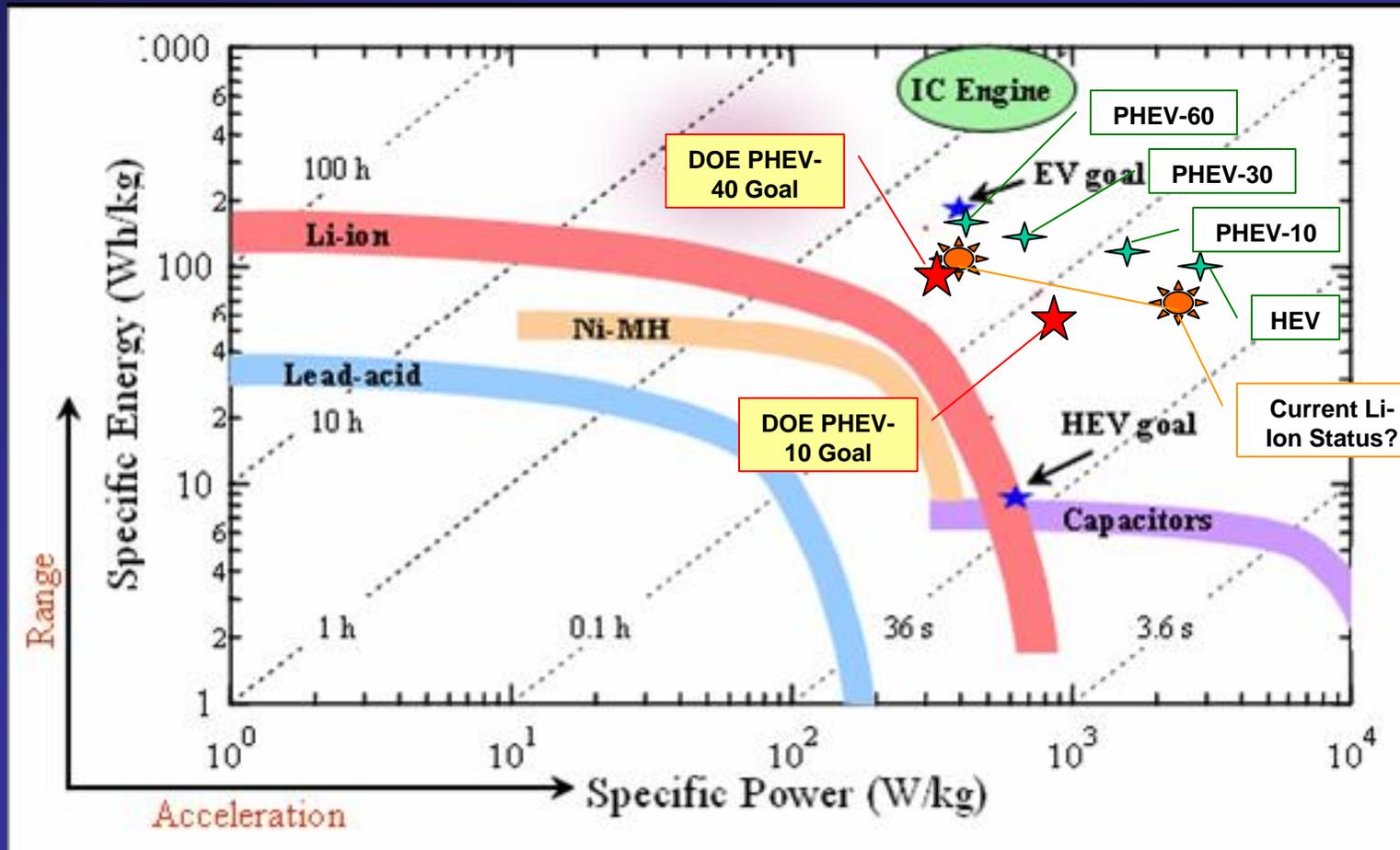
Battery Power vs. Energy Trade-off



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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Utility Factor*

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

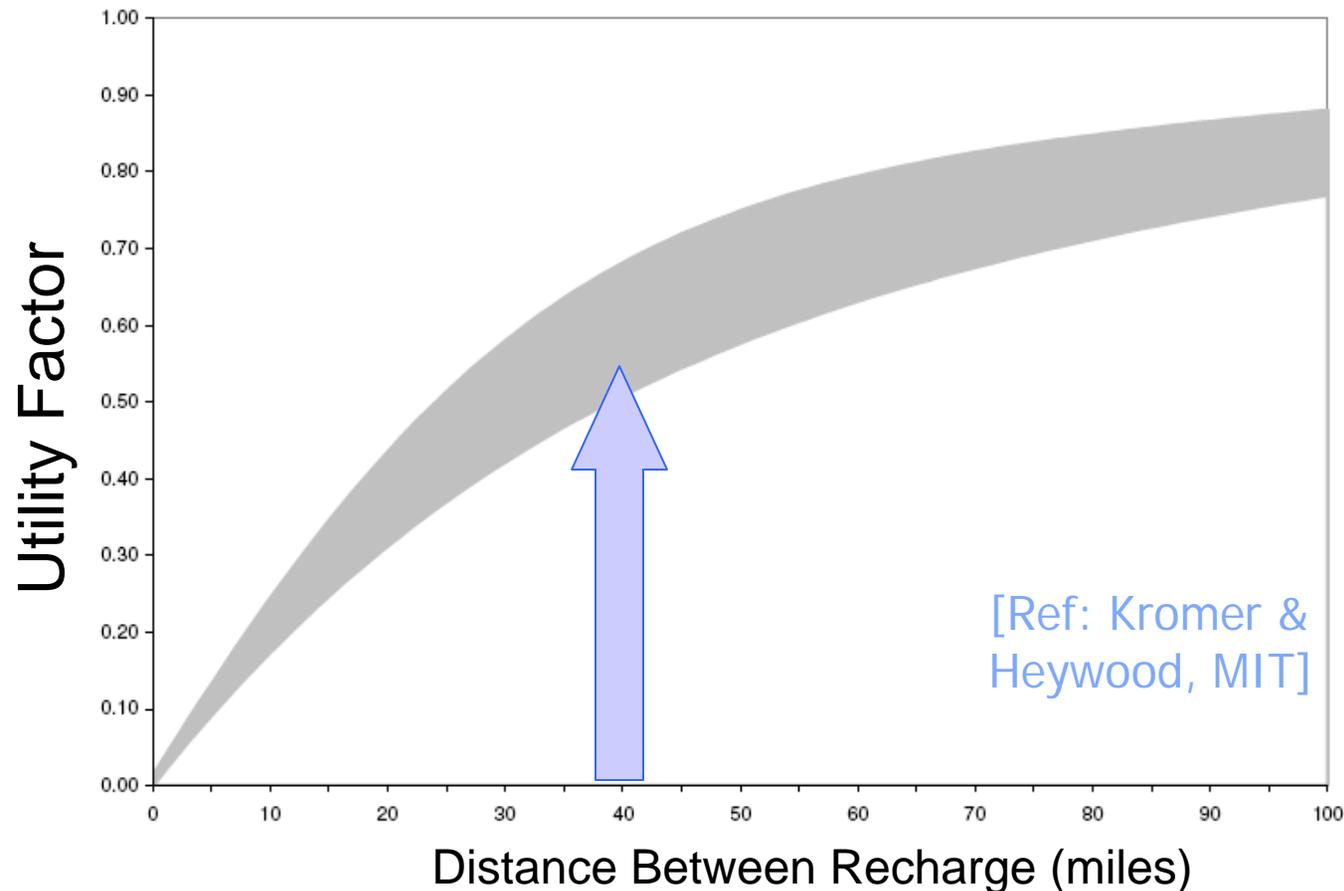
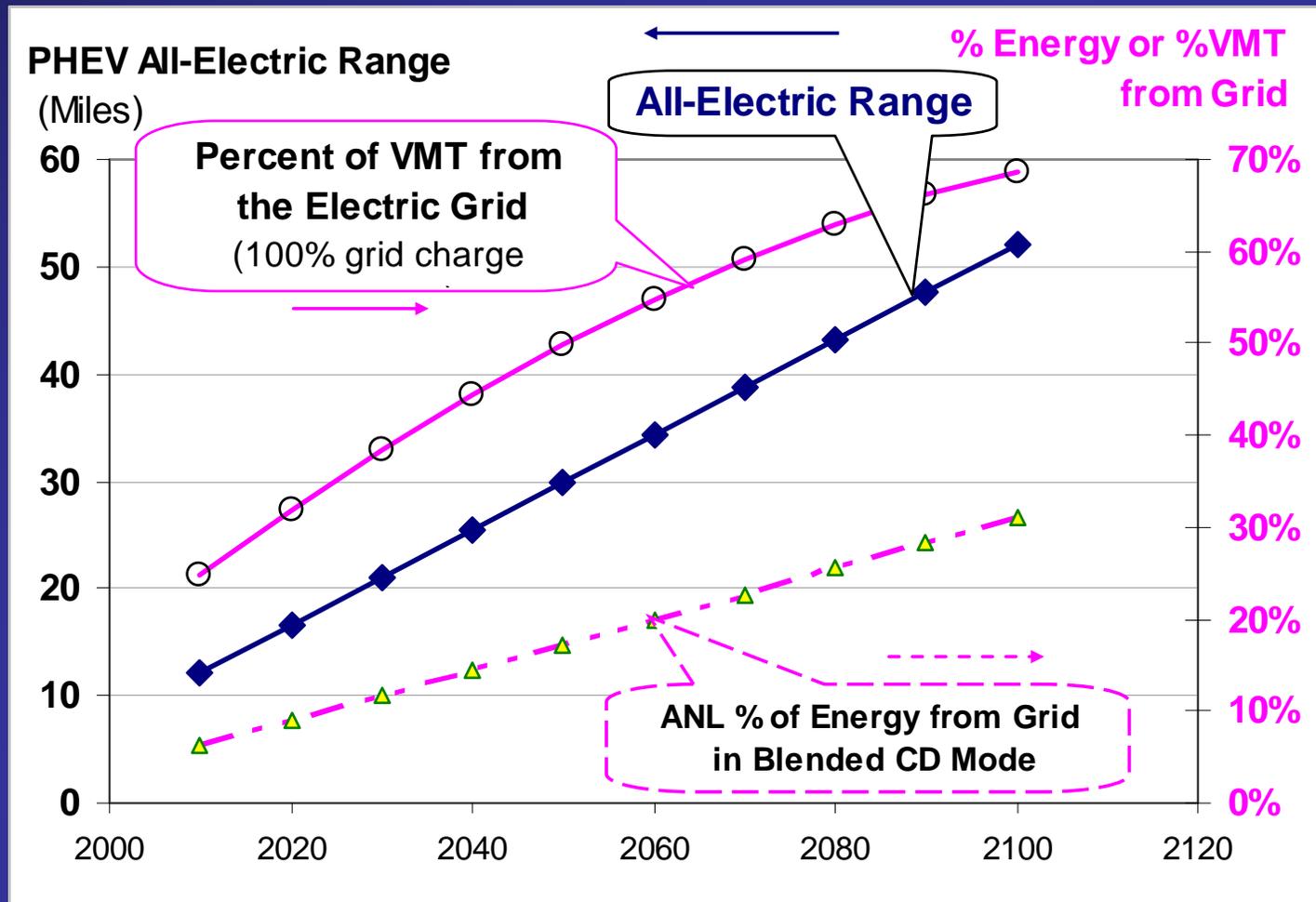


Figure 23: Estimated utility curves as a function of vehicle range: estimates from a number of different sources. Data derived from SAE J1711, EPRI 2001, Markel 2006, and ORNL 2004.

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

Plug-in Hybrid Assumptions



Google Real-World Measurement of PHEV Fuel Economy* **H₂Gen**

			
Model	Toyota Prius Plug-in	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>

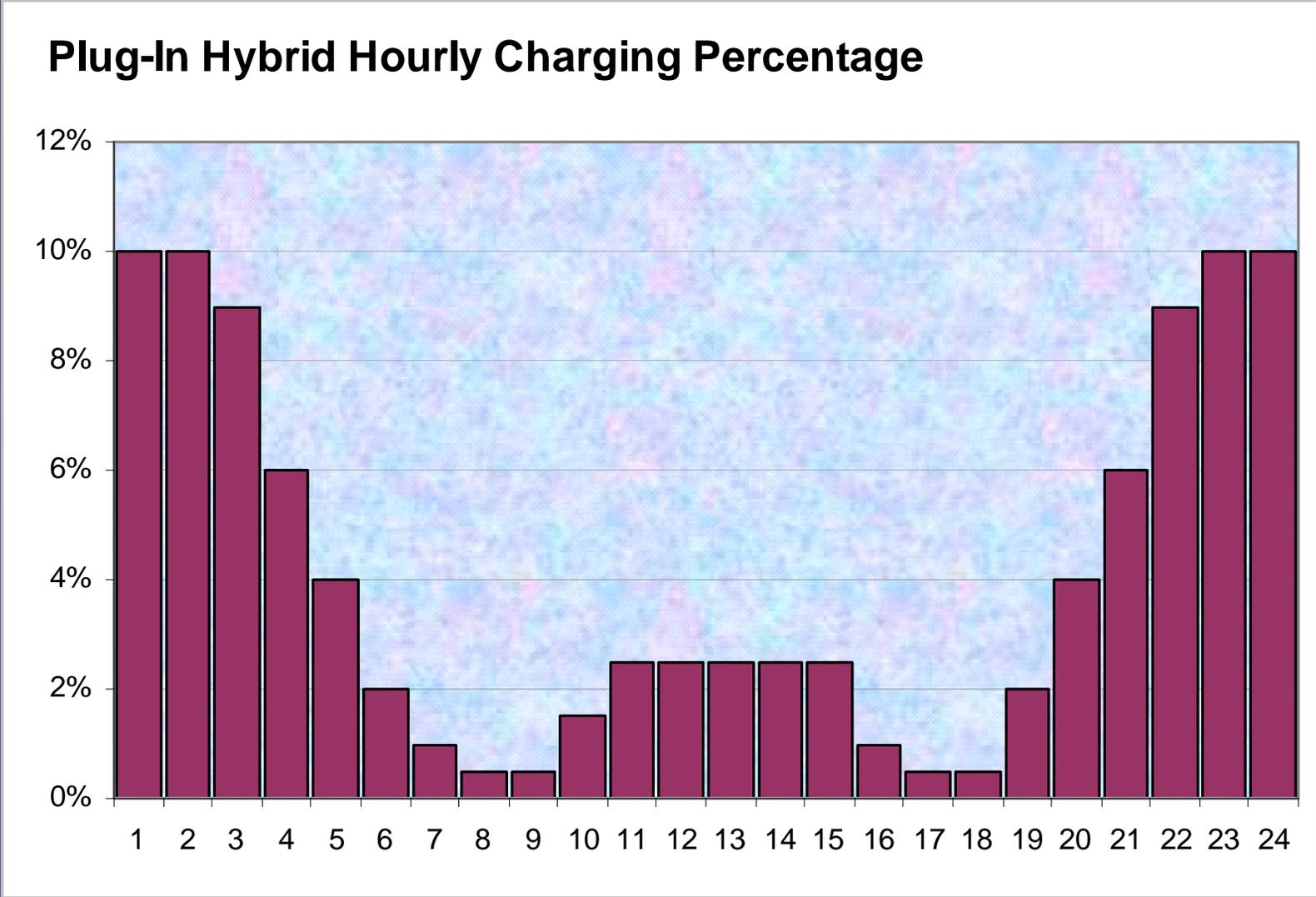
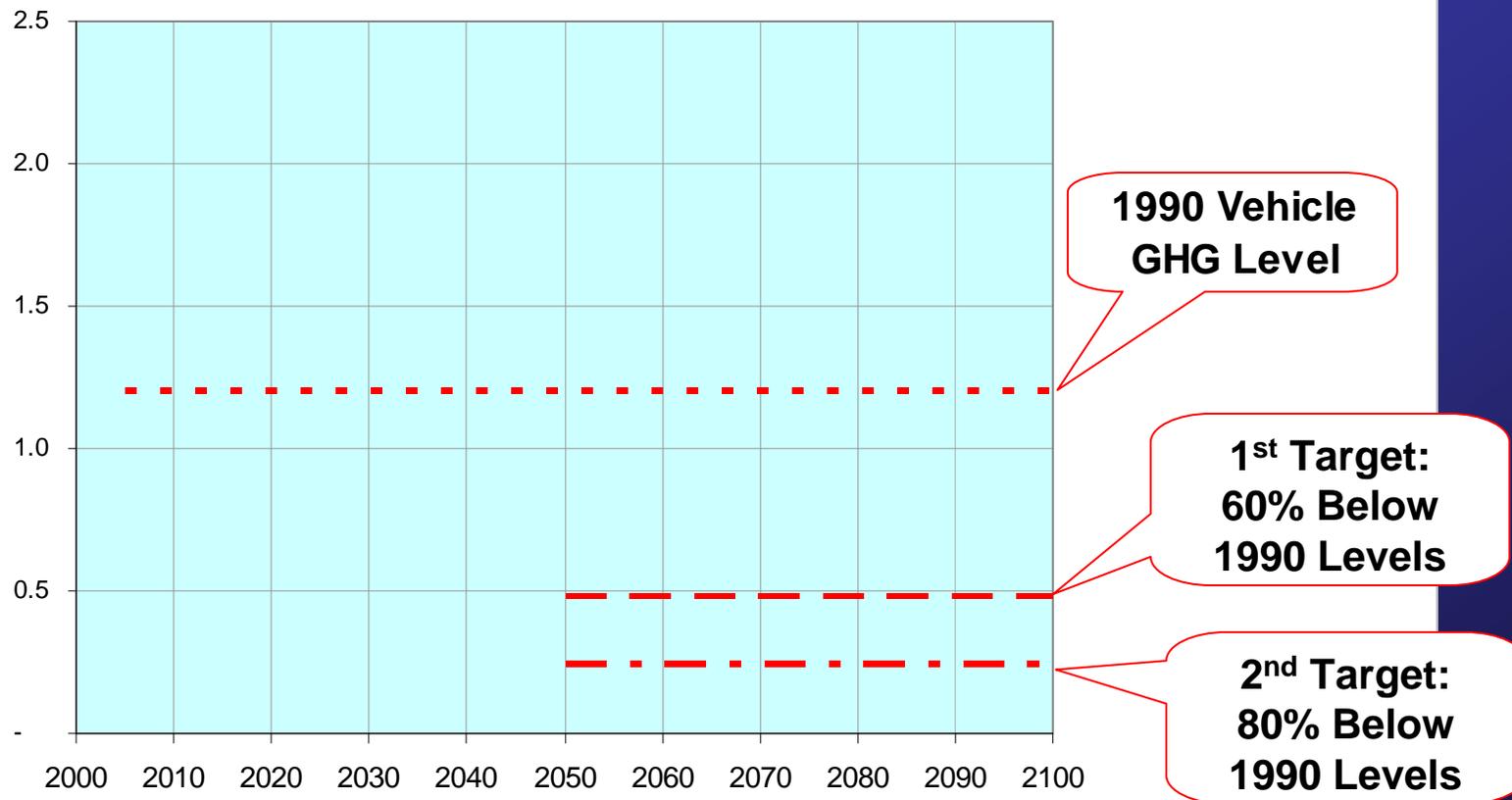


Figure 1. PHEV charging profile suggested by EPRI

1990 Baseline Transportation Greenhouse Gas (GHG) Emissions



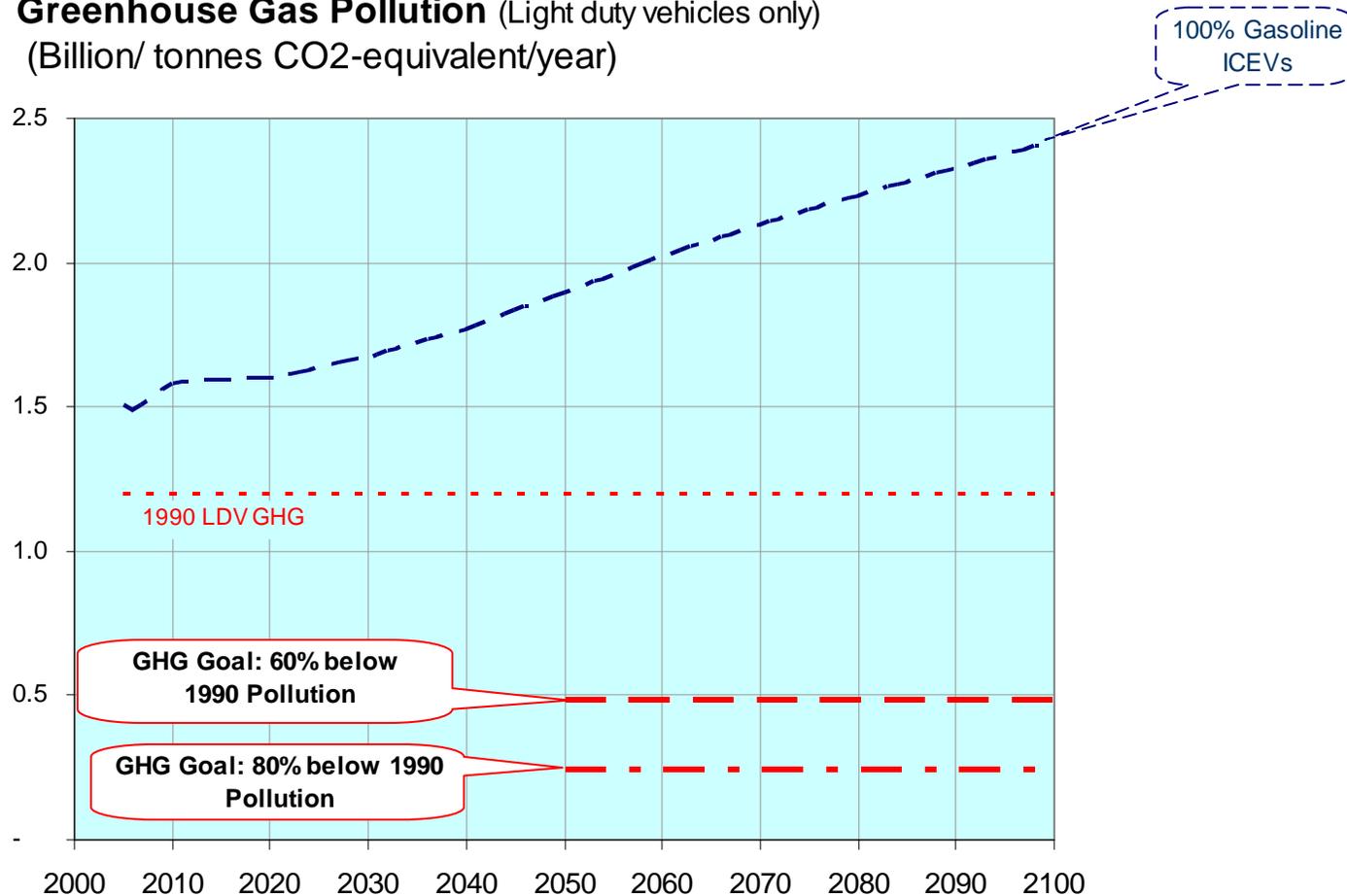
Greenhouse Gas Pollution (Light duty vehicles only)
(Billion metric tonnes CO₂-equivalent/year)



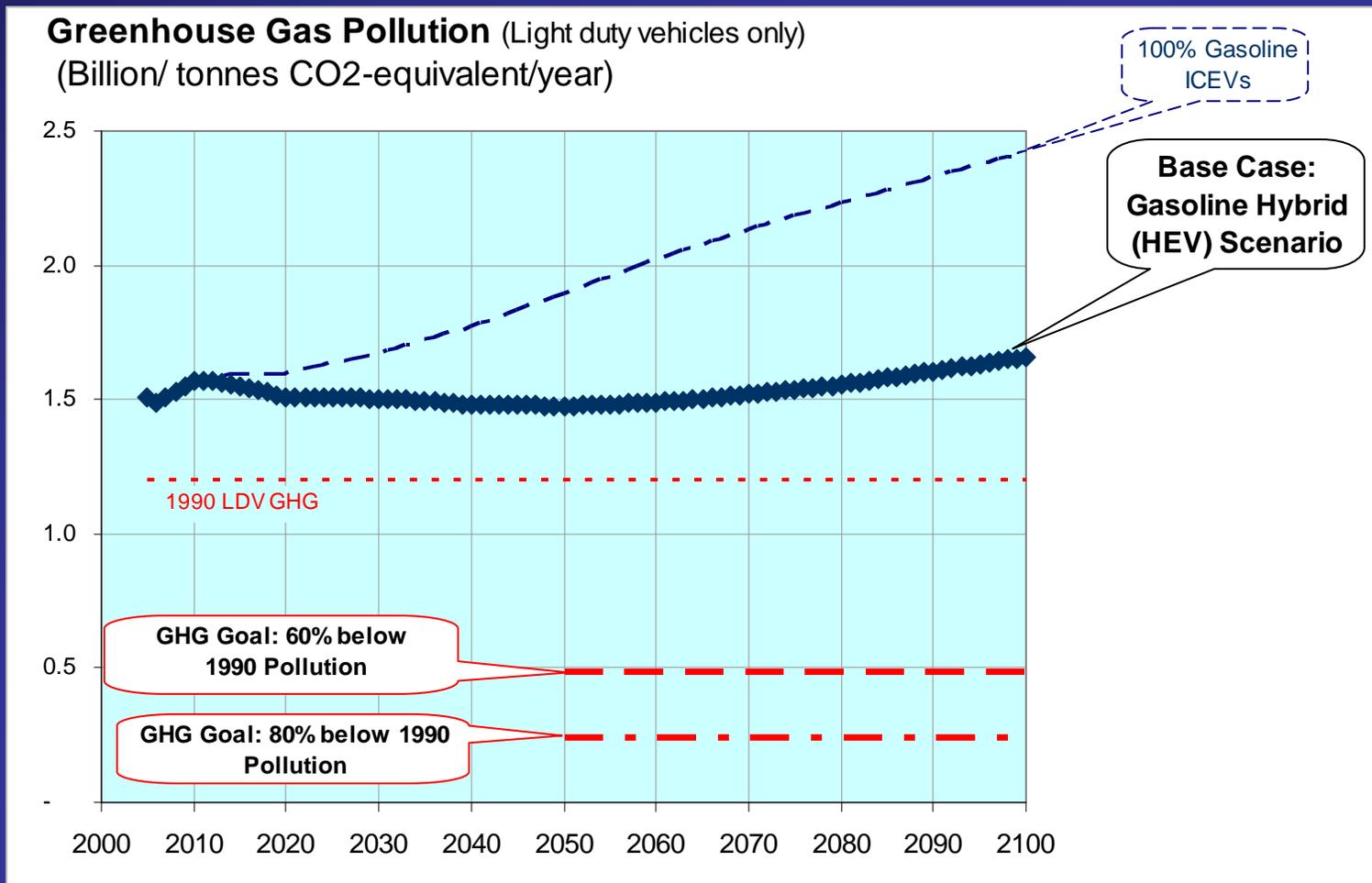


GHG Reference Case: 100% Gasoline Cars

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



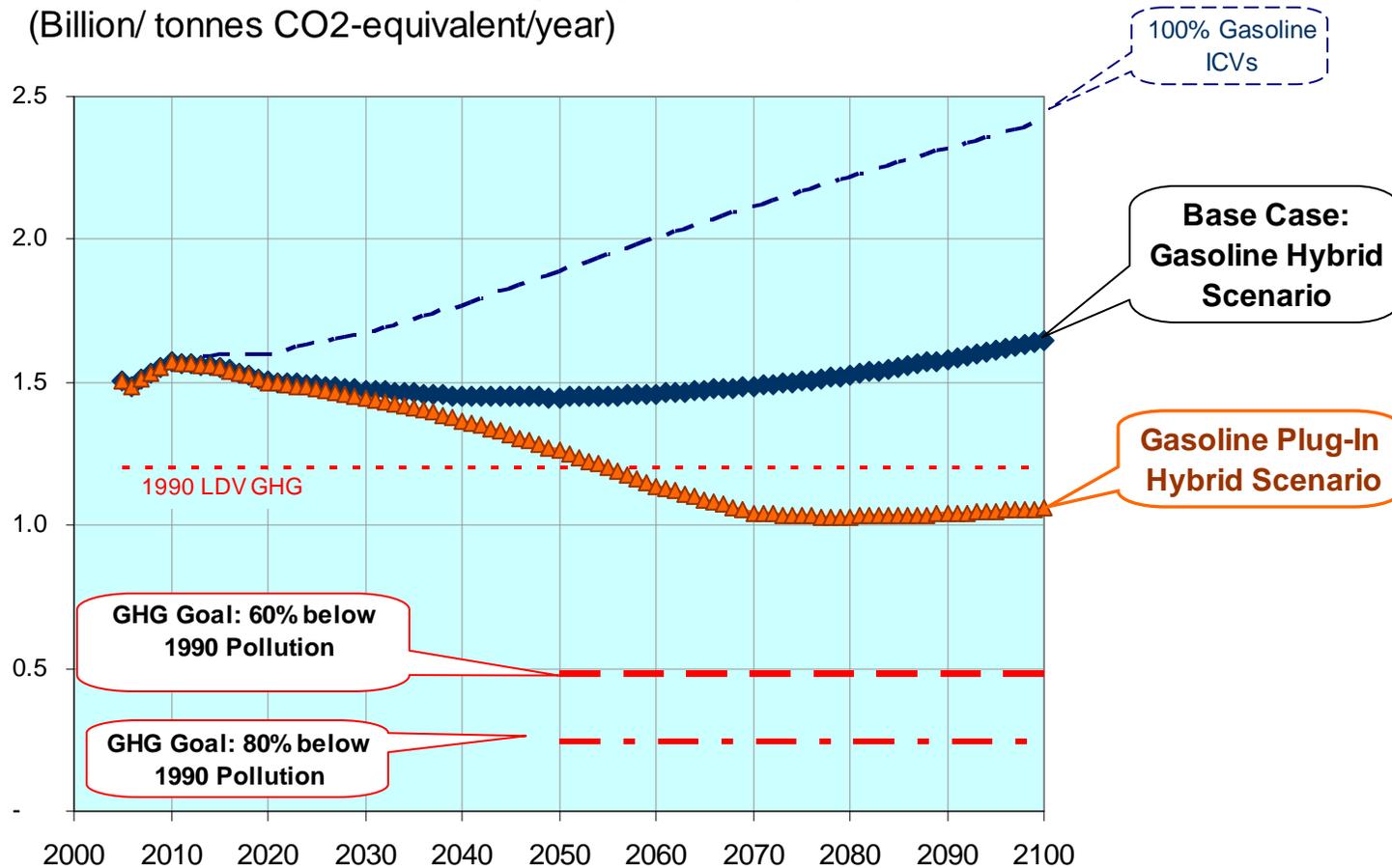
GHG Base Case: Gasoline Hybrid Electric Vehicles (HEVs)



GHG: Gasoline Plug-in Hybrid Electric Vehicles (PHEVs) (75% night-time charging access)



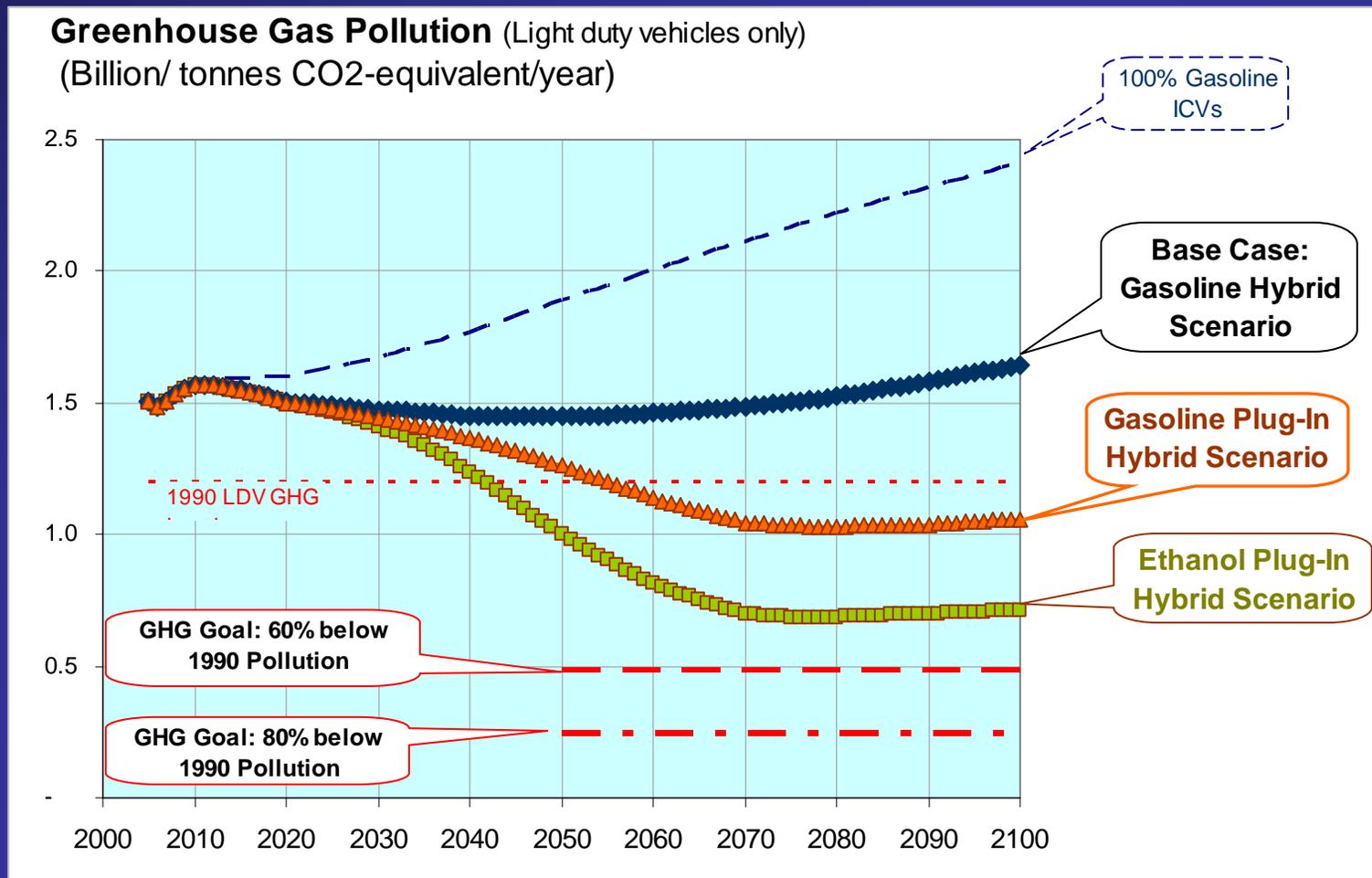
Greenhouse Gas Pollution (Light duty vehicles only)
(Billion/ tonnes CO₂-equivalent/year)





GHG: Biofuel Plug-In Hybrids

(90 Billion gallons/year* Cellulosic Ethanol)

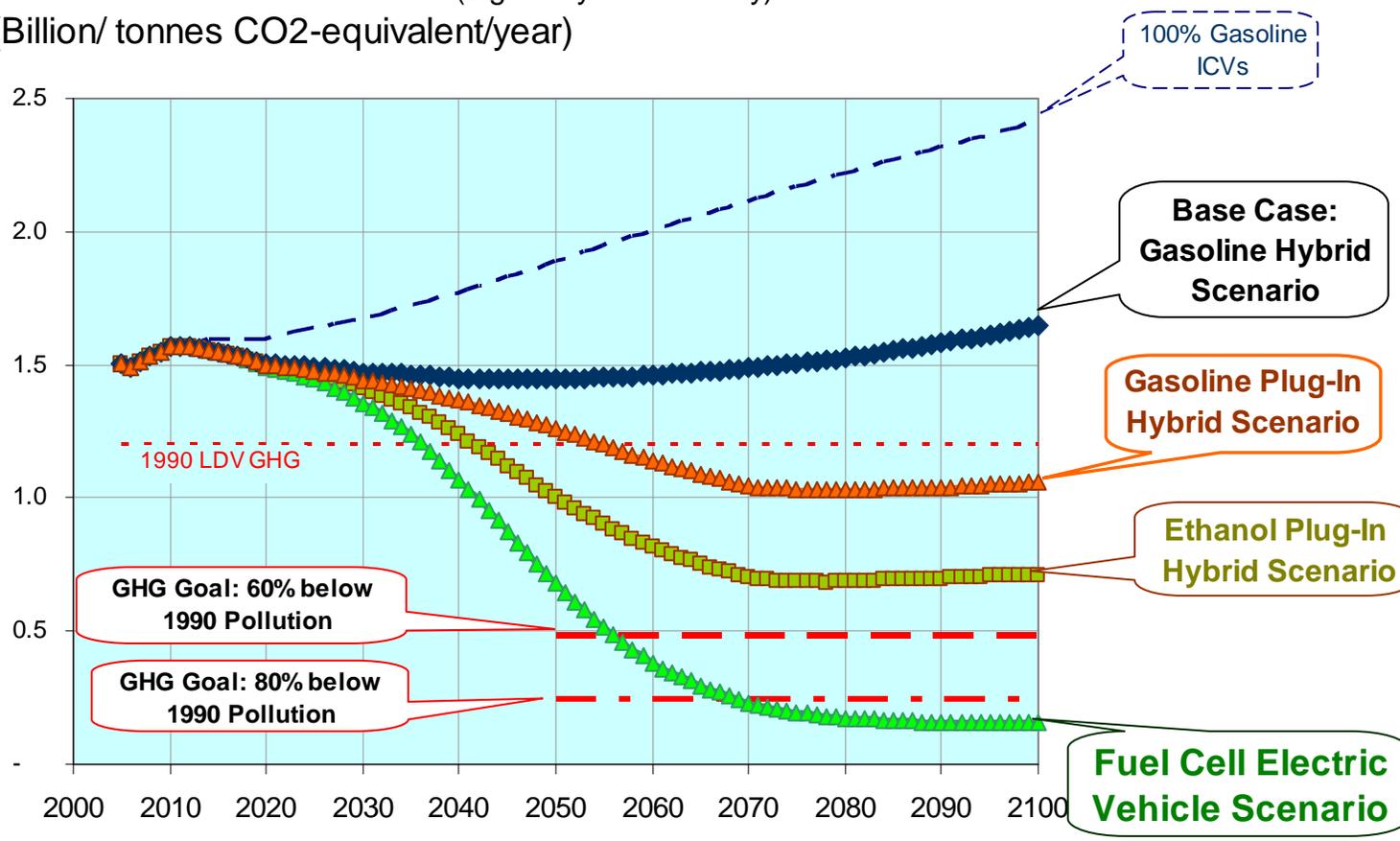


*Sandia-Livermore estimates 90 B gallons/yr potential; NRC uses 60 B gallons/yr maximum; current production of ethanol: 8 billion gallons/year; no limit on availability of night-time charging outlets

GHG: Fuel Cell Vehicles



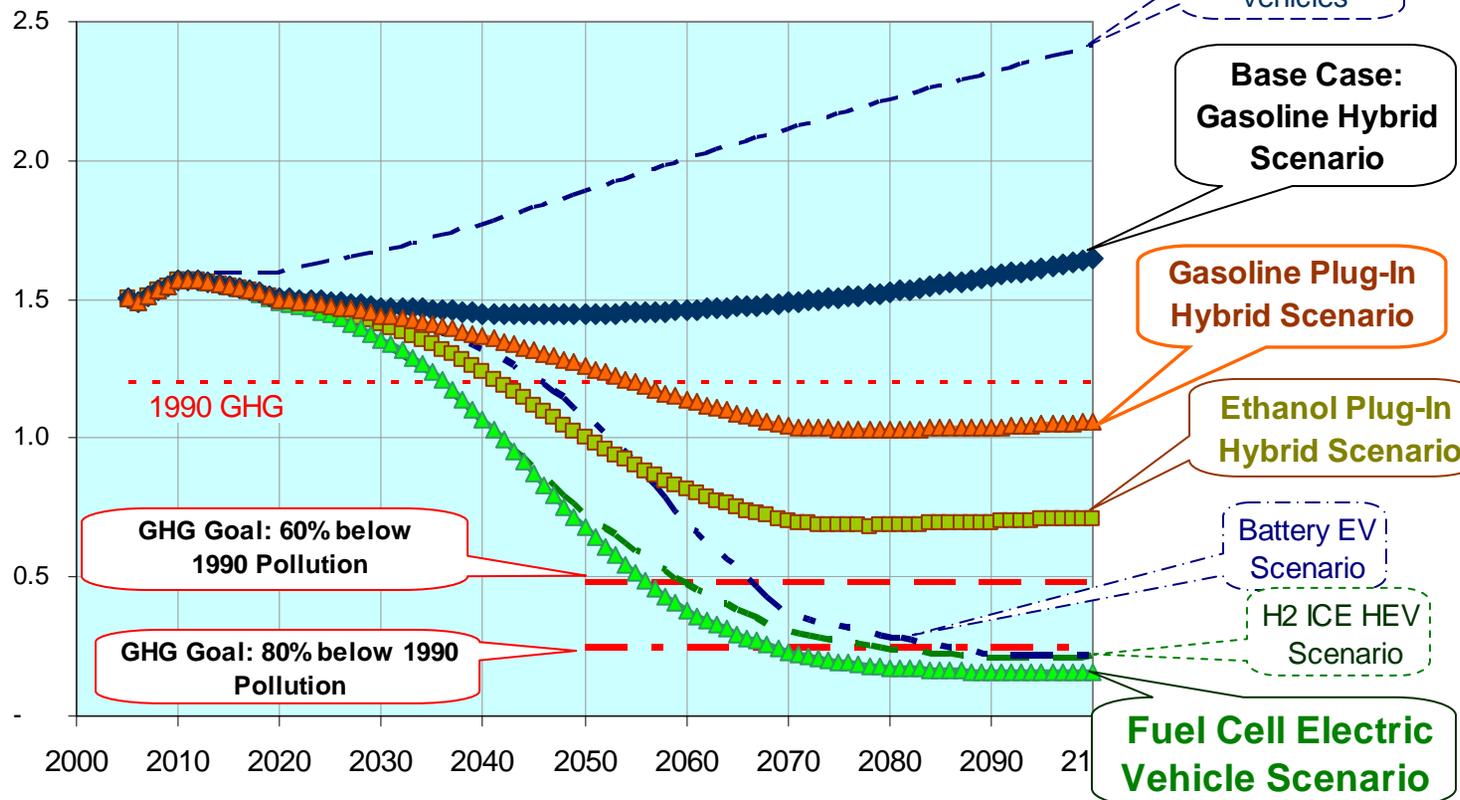
Greenhouse Gas Pollution (Light duty vehicles only)
(Billion/ tonnes CO₂-equivalent/year)



GHG: H₂ ICE HEV & Battery EV



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



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

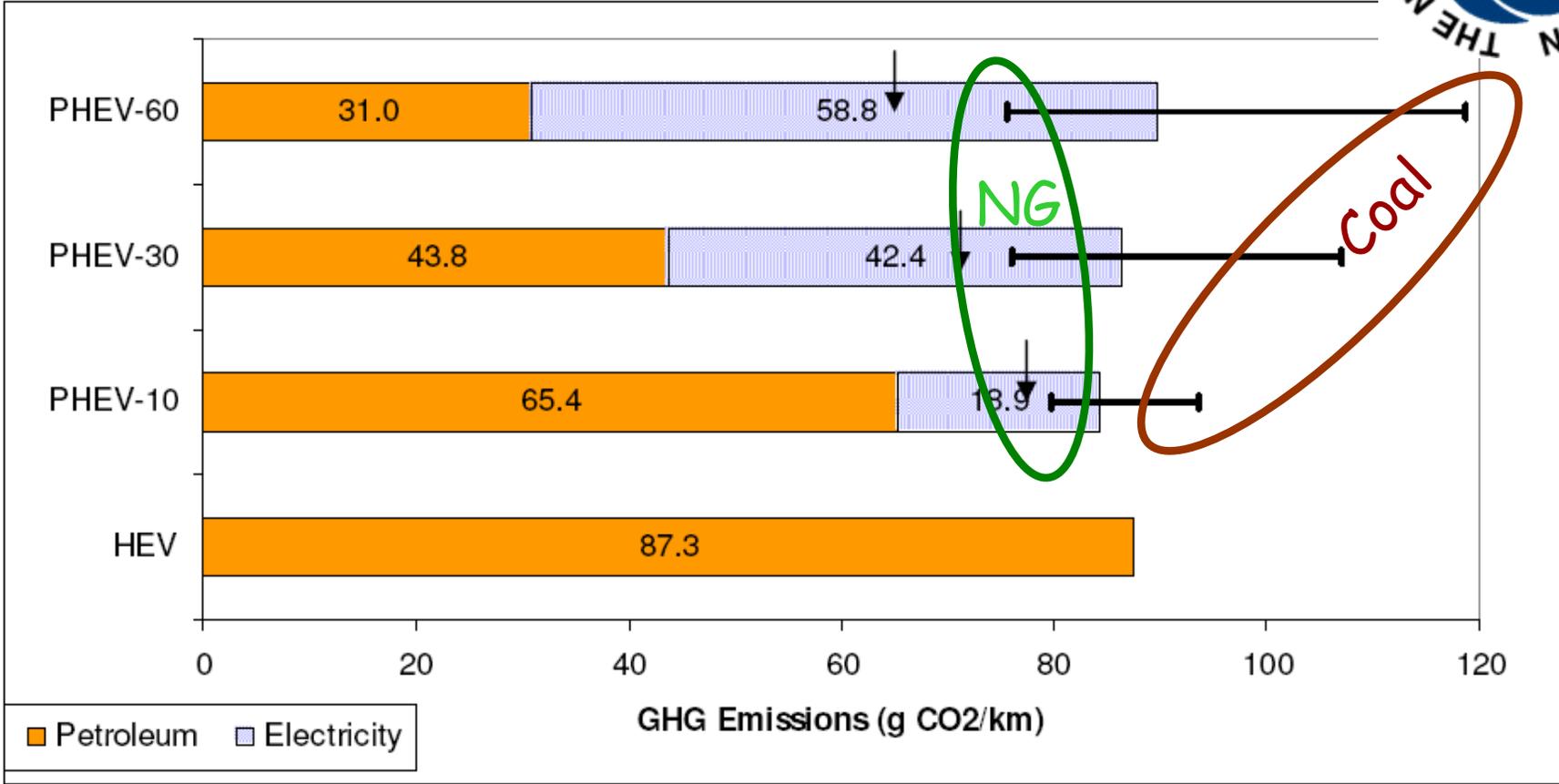


Figure 38: Breakdown of GHG emissions for the hybrid vehicle and plug-in hybrids with varying range. The low-end of the uncertainty bar corresponds to natural gas generation; the high-end corresponds to coal; and the base case corresponds to the average grid. The arrows indicate the emissions rate of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

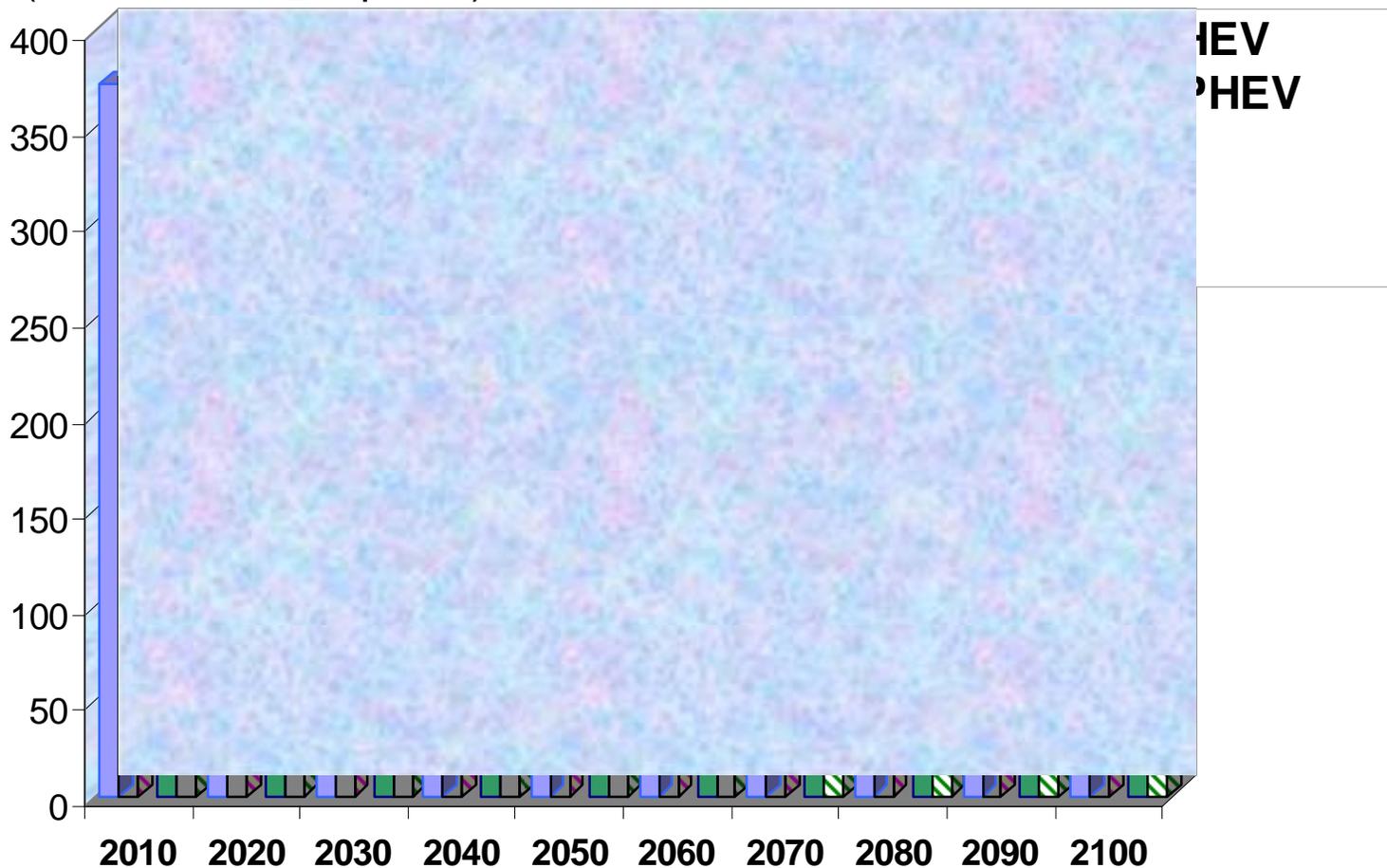
“Clean Grid” = 50% nuclear + renewables; 15% advanced NG CC & 35% advanced coal

To Plug or Not to Plug?



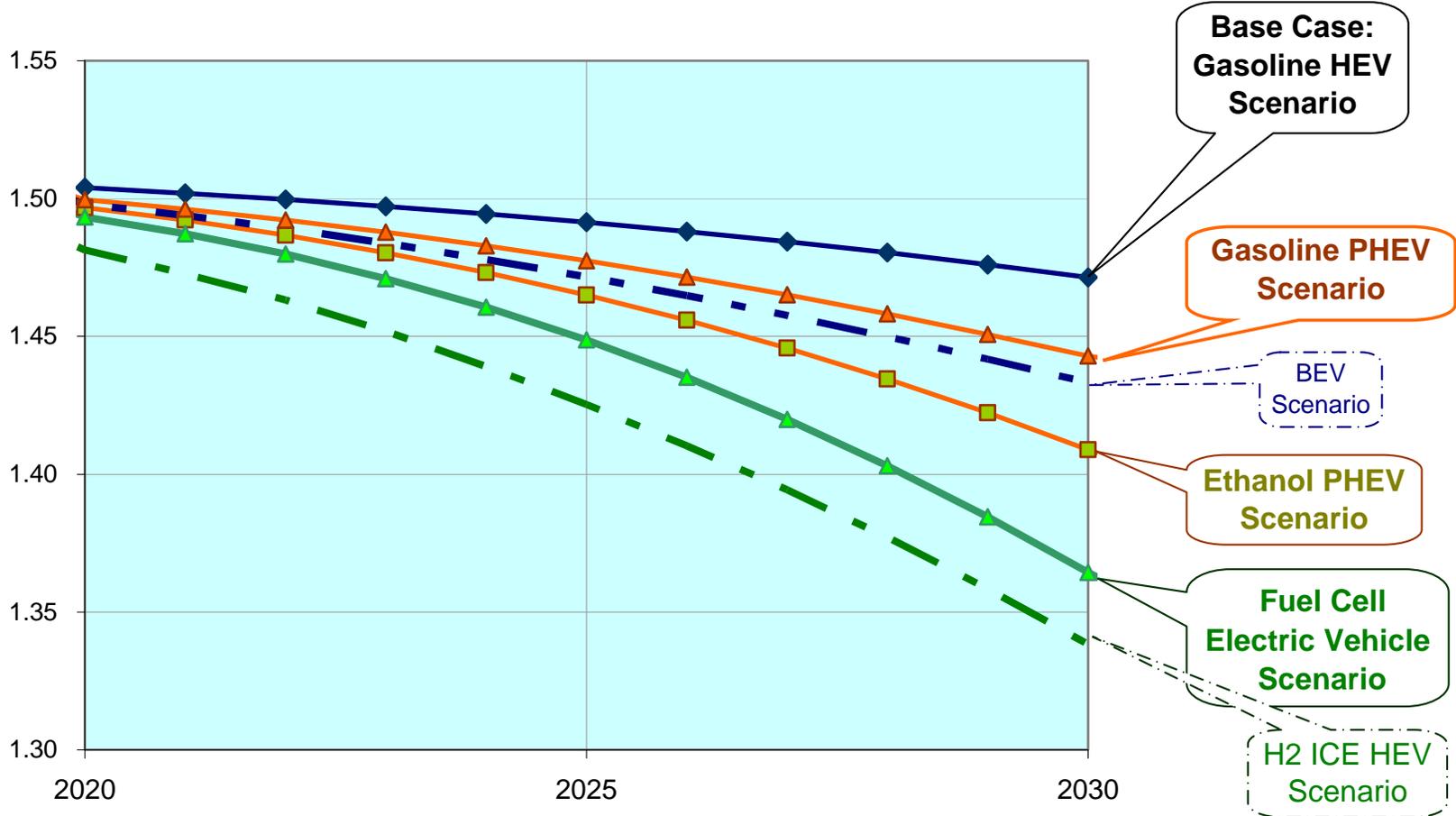
Greenhouse Gas Emissions per Car
(Grams of CO₂-eq./mile)

West Coast Marginal Grid Mix
with Carbon Constraints



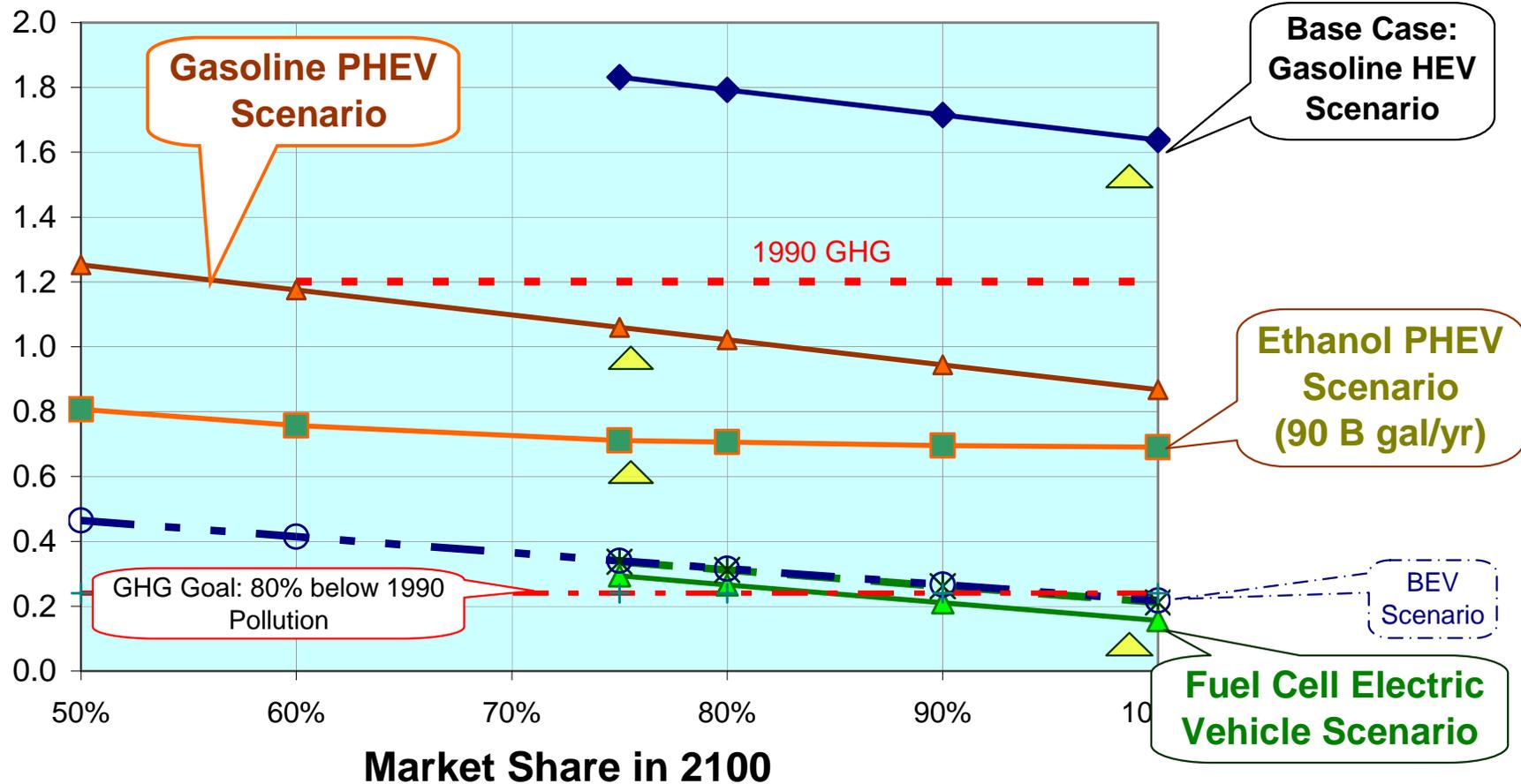
Early (2020 to 2030) GHGs

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



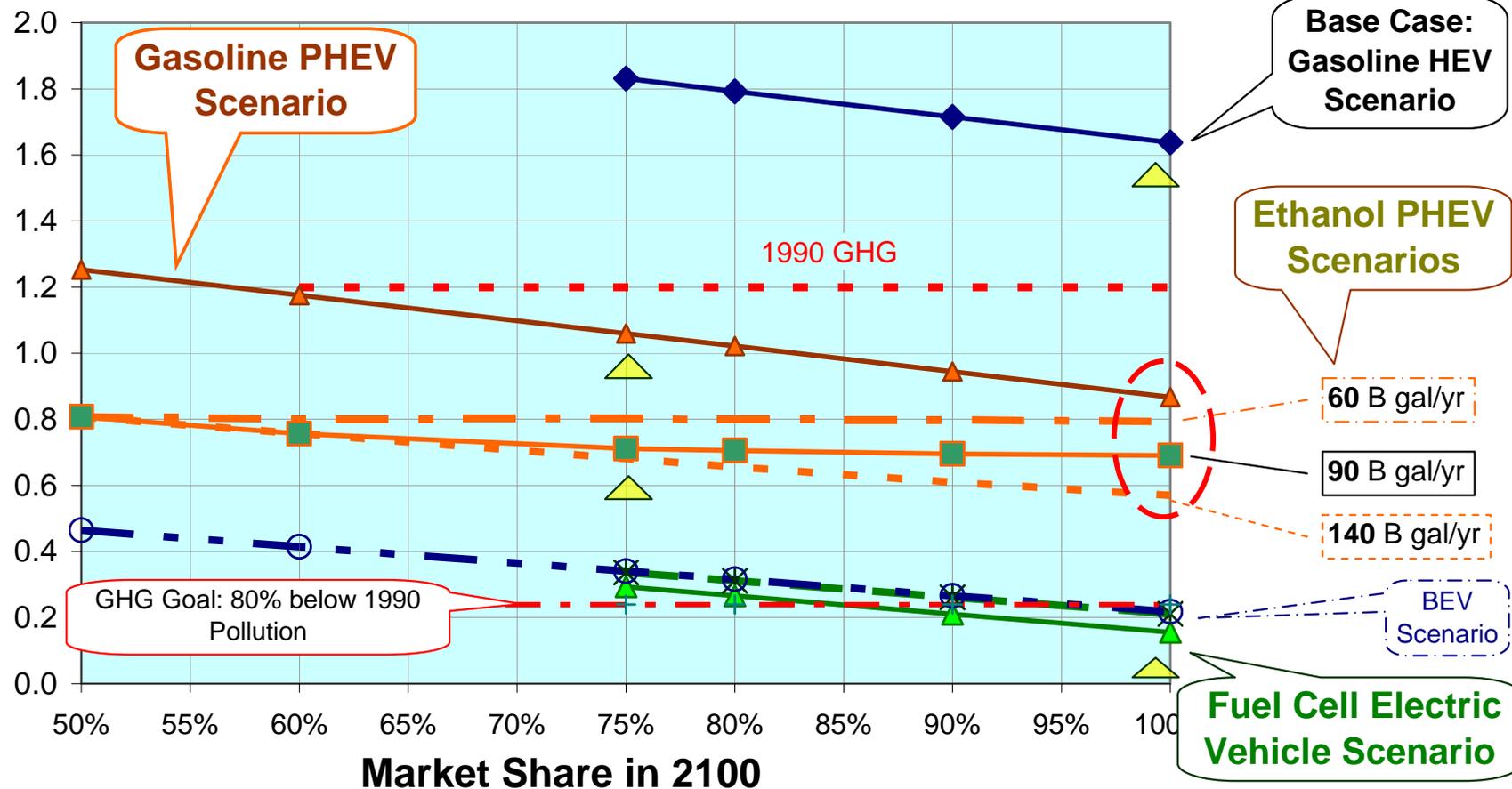
GHG Sensitivity to Market Share

Greenhouse Gas Pollution in 2100 (Light duty vehicles only)
 (Billion metric tonnes CO₂-equivalent/year)



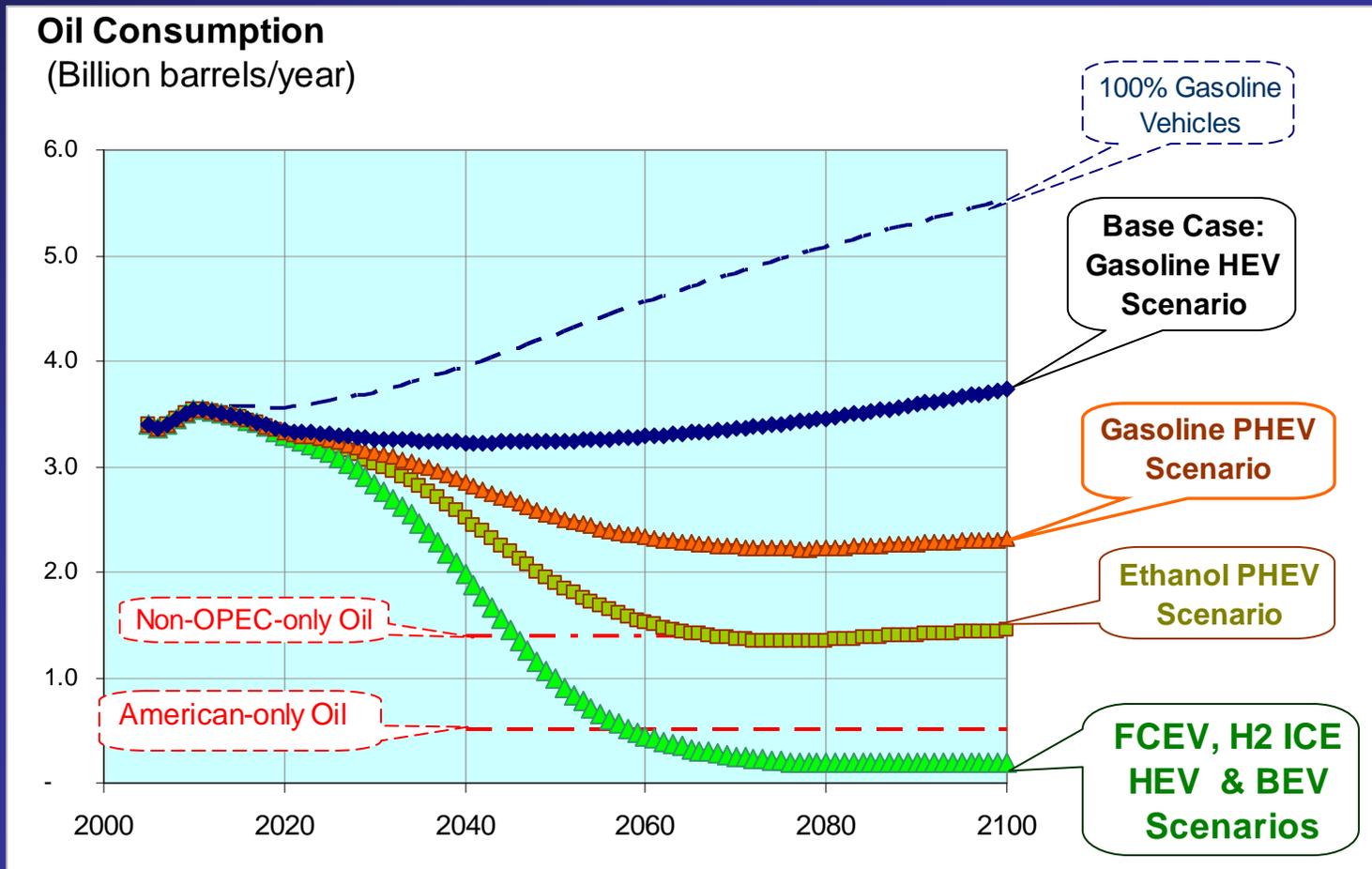
GHG Sensitivity to Market Share & Ethanol Capacity

Greenhouse Gas Pollution in 2100 (Light duty vehicles only)
 (Billion metric tonnes CO₂-equivalent/year)





Oil Consumption

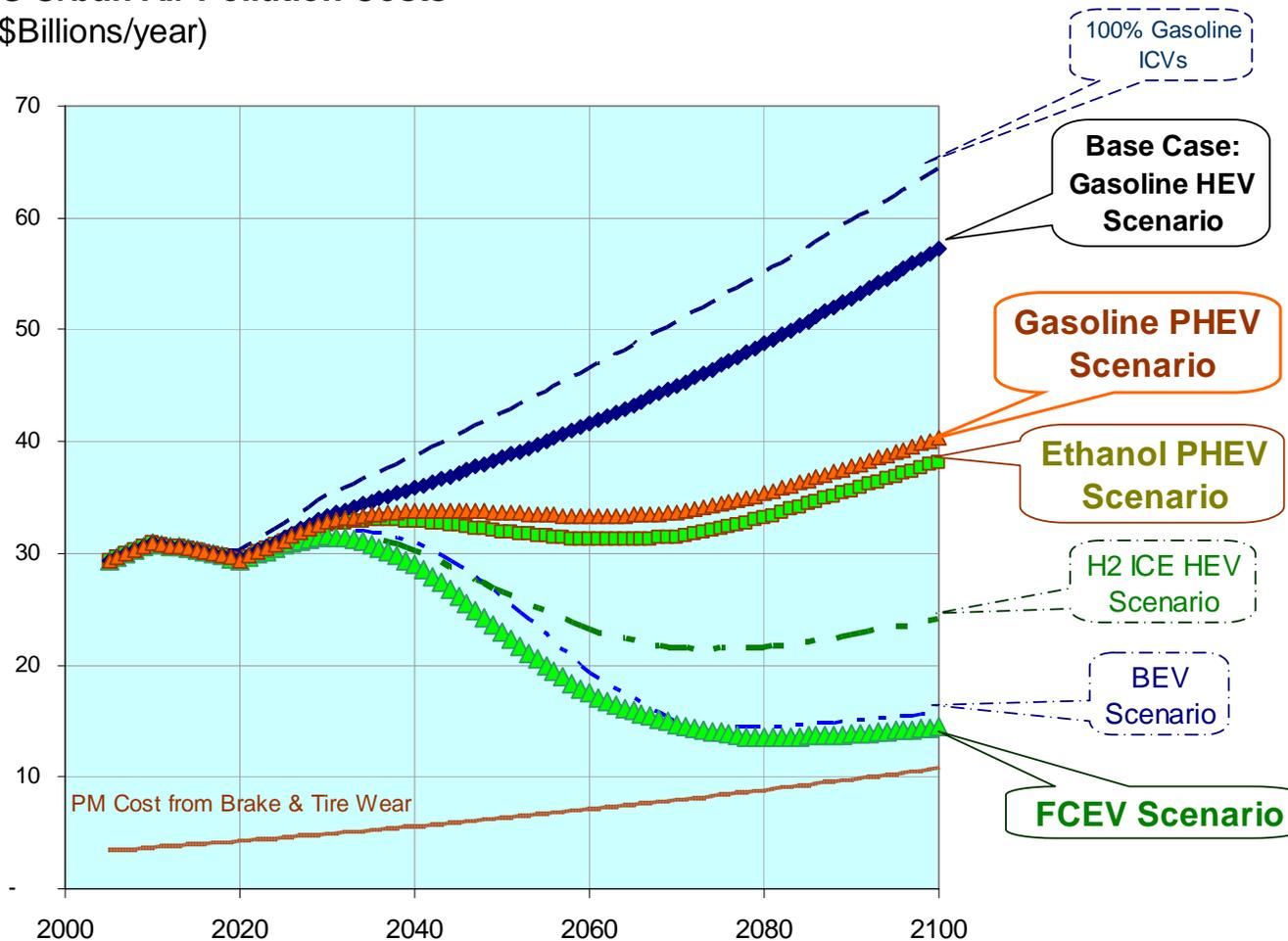


Urban Air Pollution Costs

(with H2 ICE HEVs and BEVs)



US Urban Air Pollution Costs
(\$Billions/year)





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

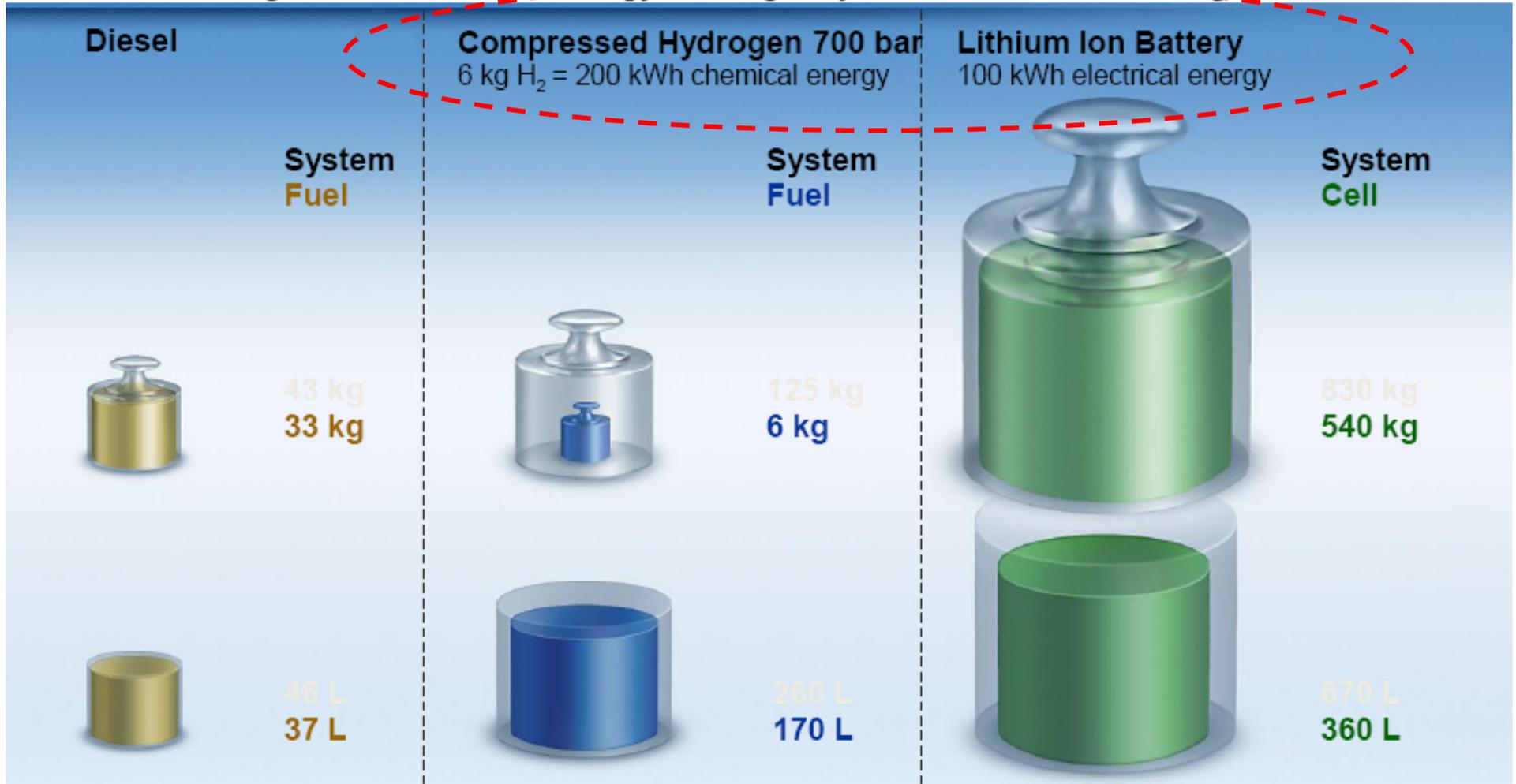
* Or Hydrogen ICE HEVs



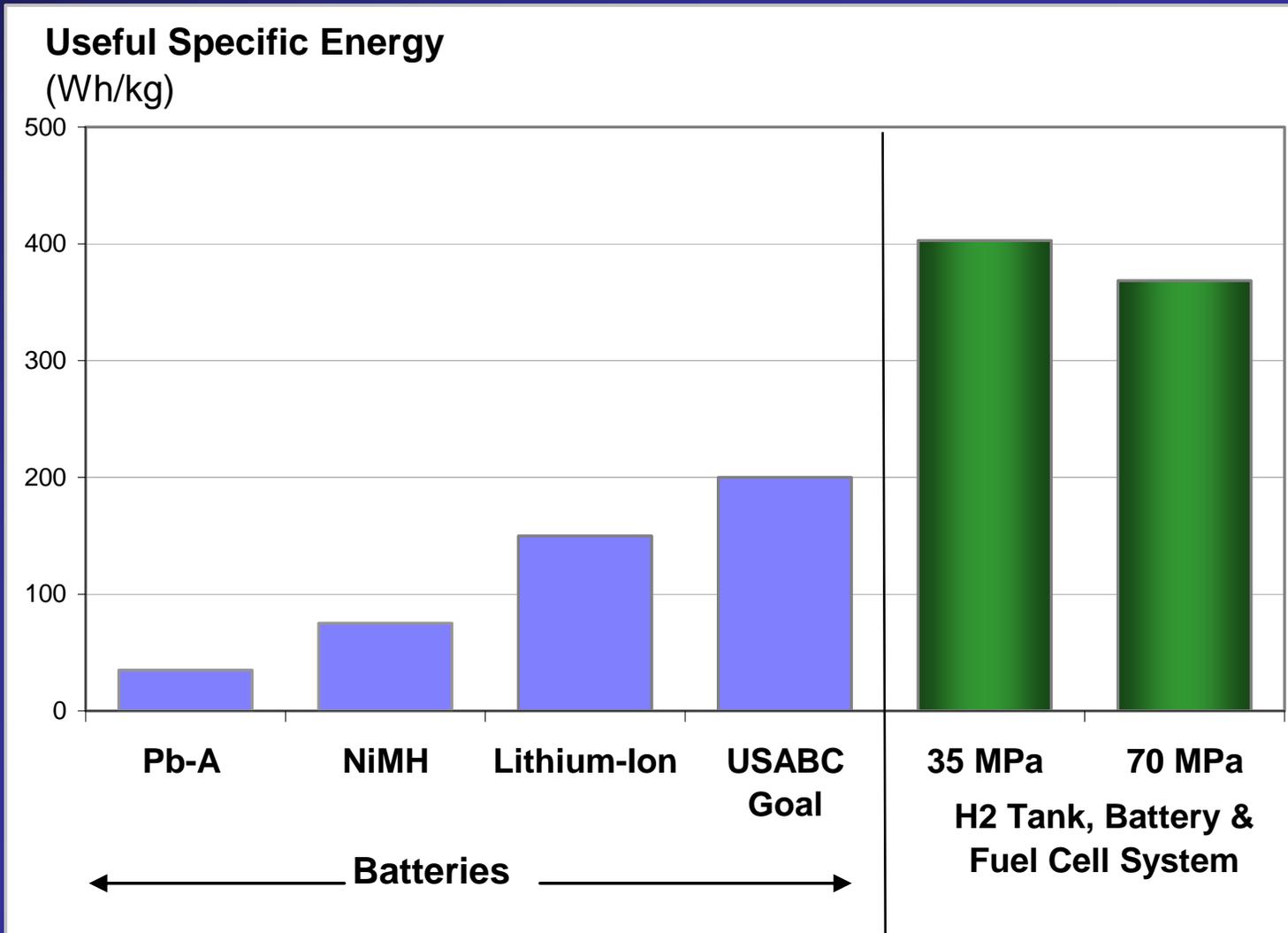
Energy Carrier Properties: Onboard Storage

Why is petroleum the dominant transportation fuel?

Weight & Volume of Energy Storage System for 500 km Range

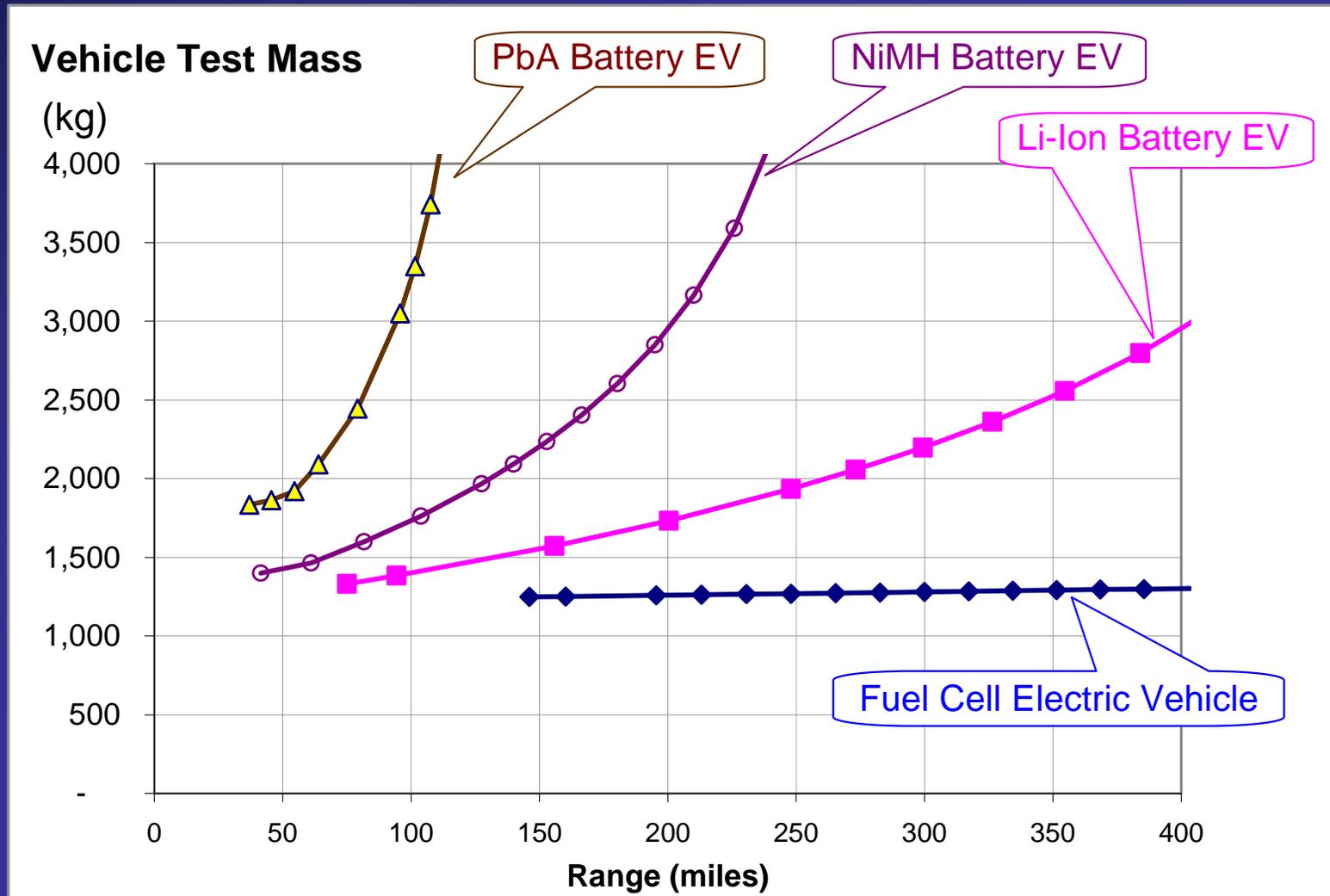


Specific Energy Comparison

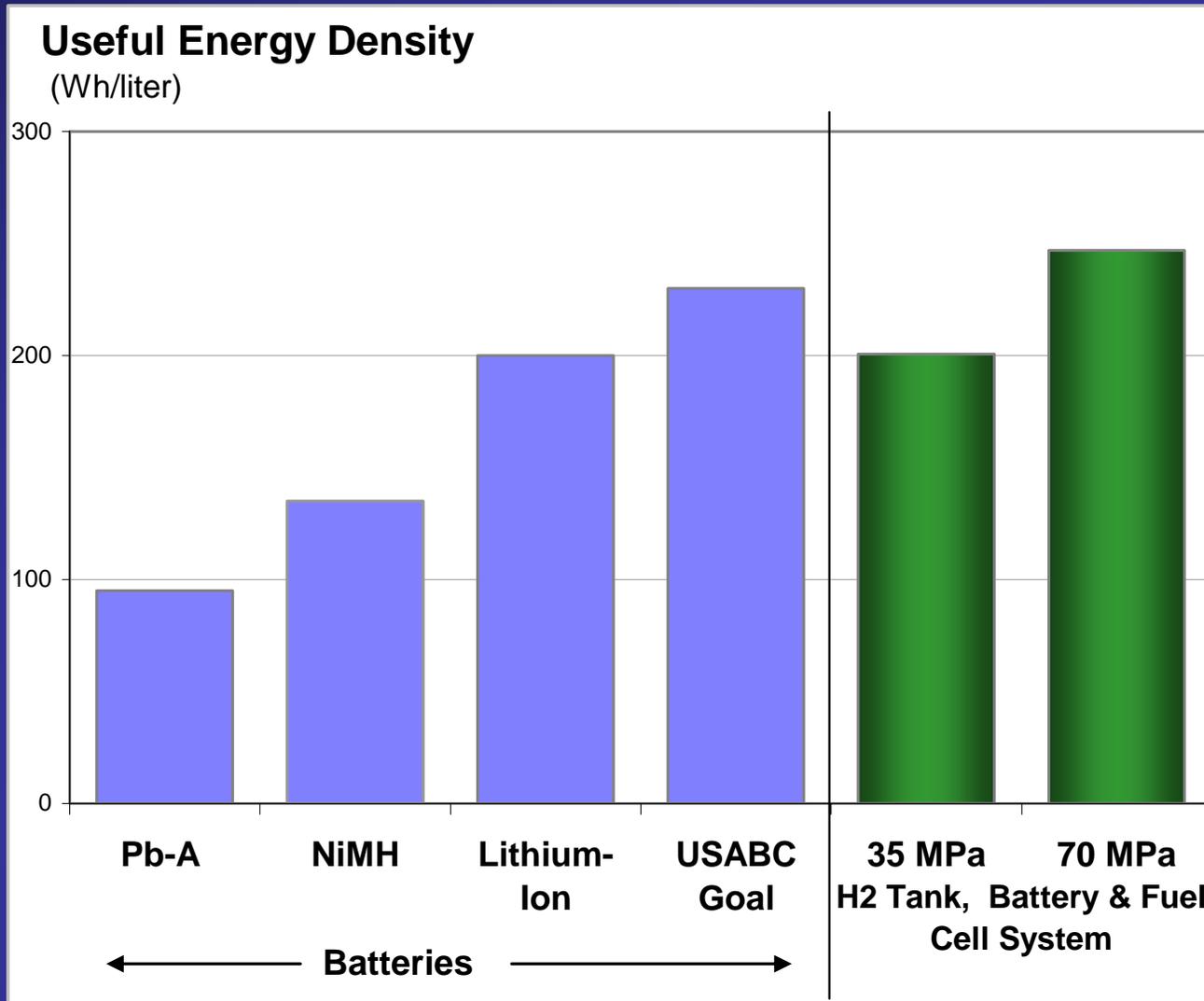


Batteries Weigh More

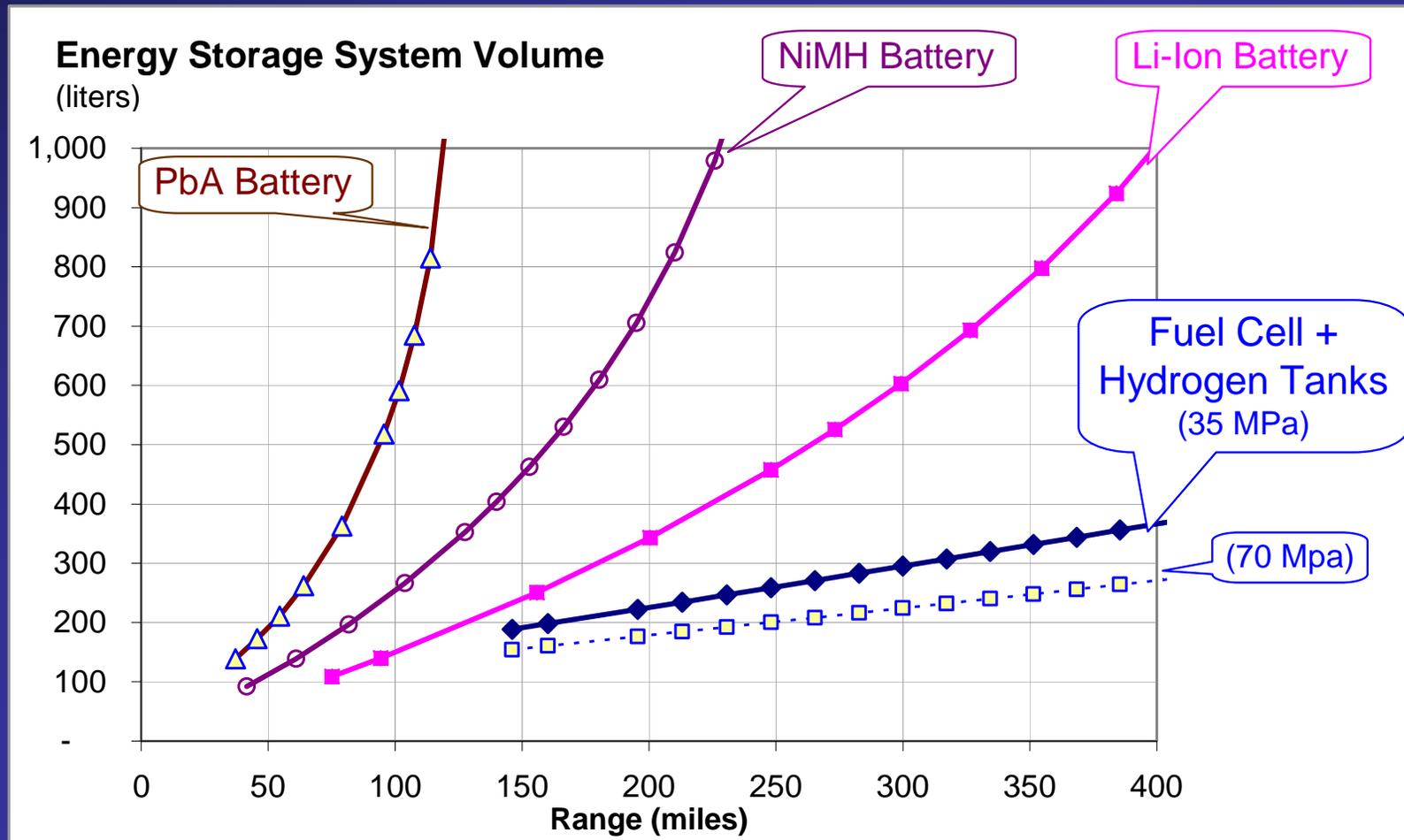
(Effects of weight compounding)



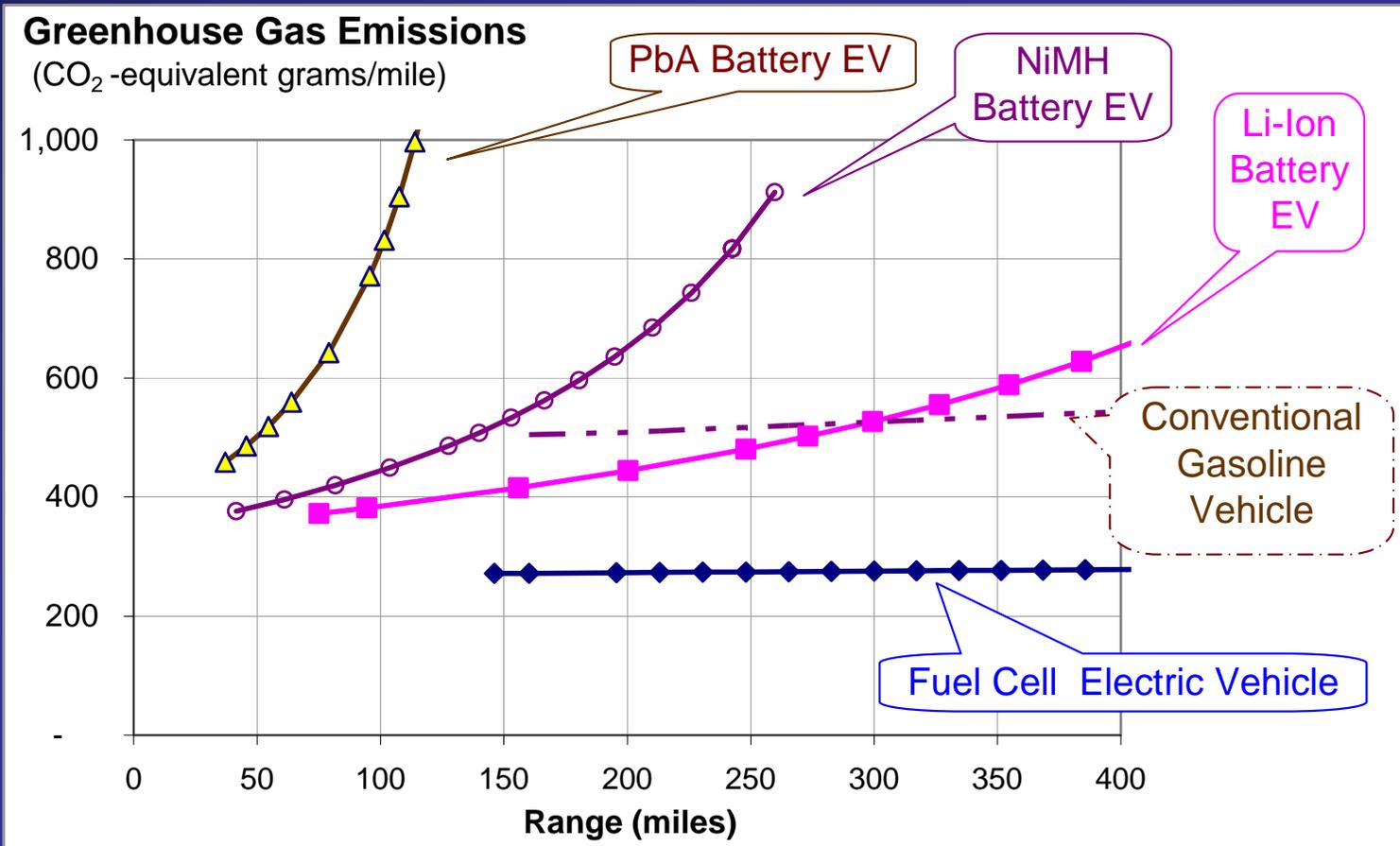
Useful Energy Density



Batteries also take up more space:



BEVs will initially generate more Greenhouse Gases than FCEVs*

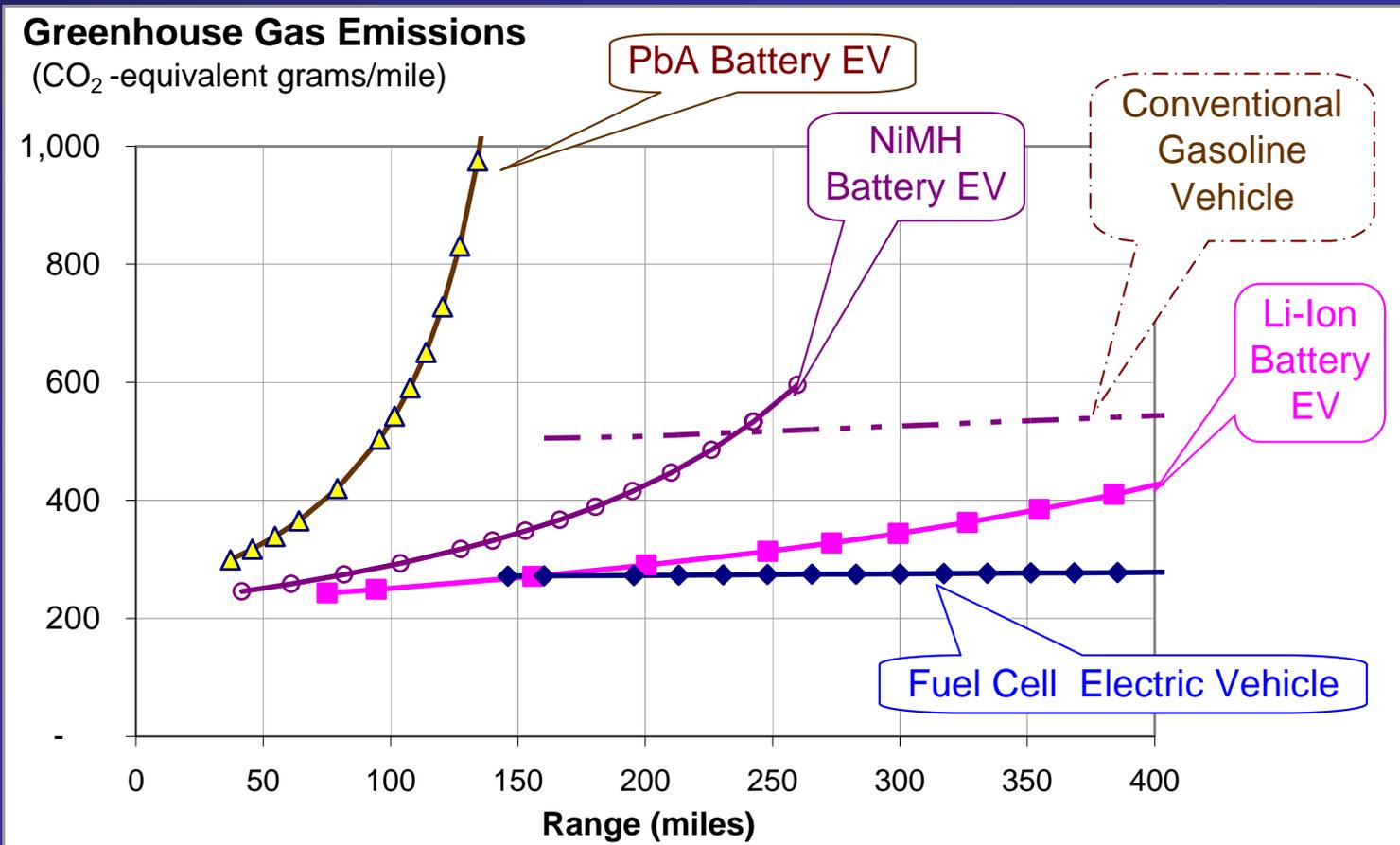


Grid Mix: US

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*

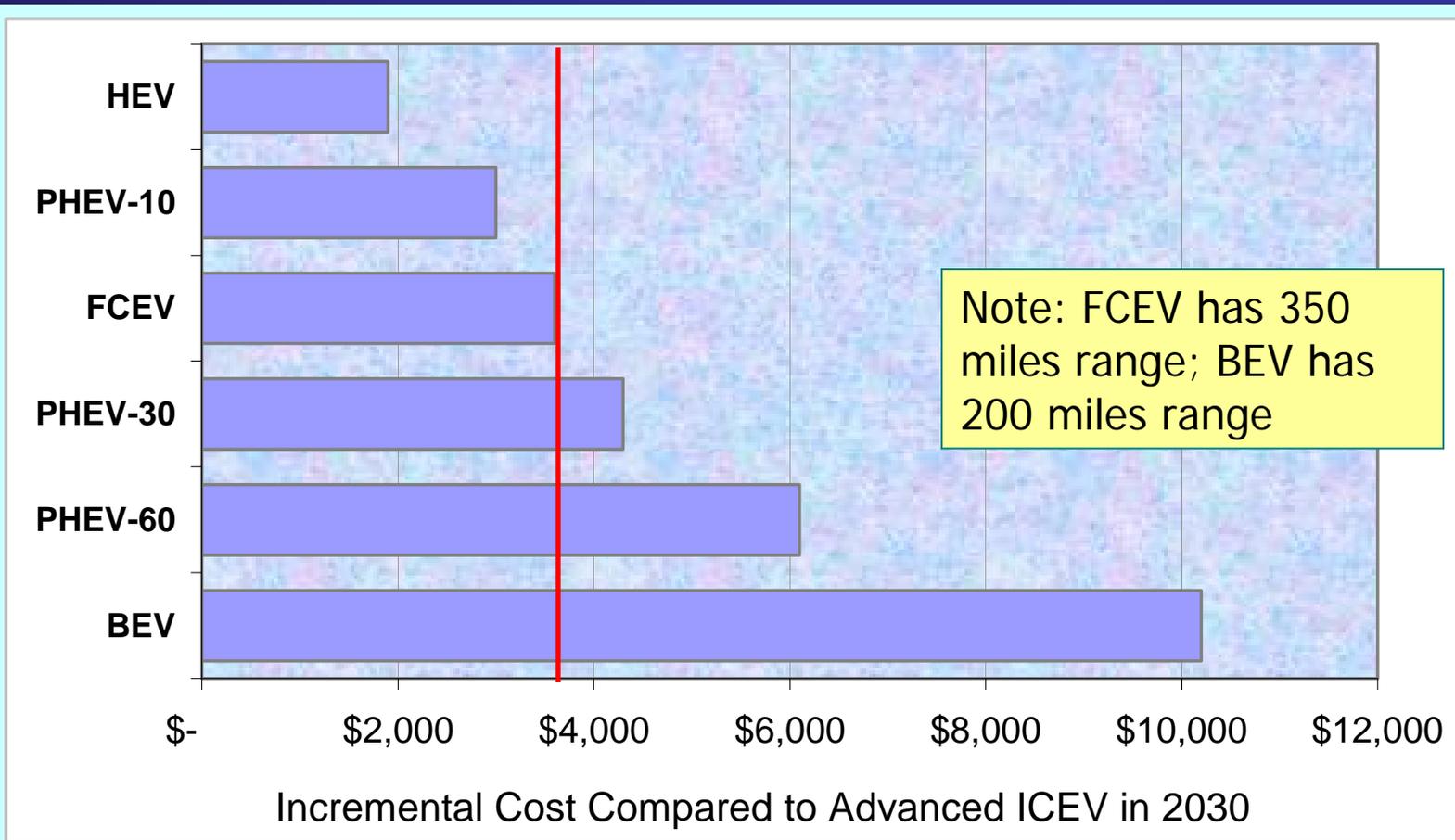


Grid Mix: California

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)



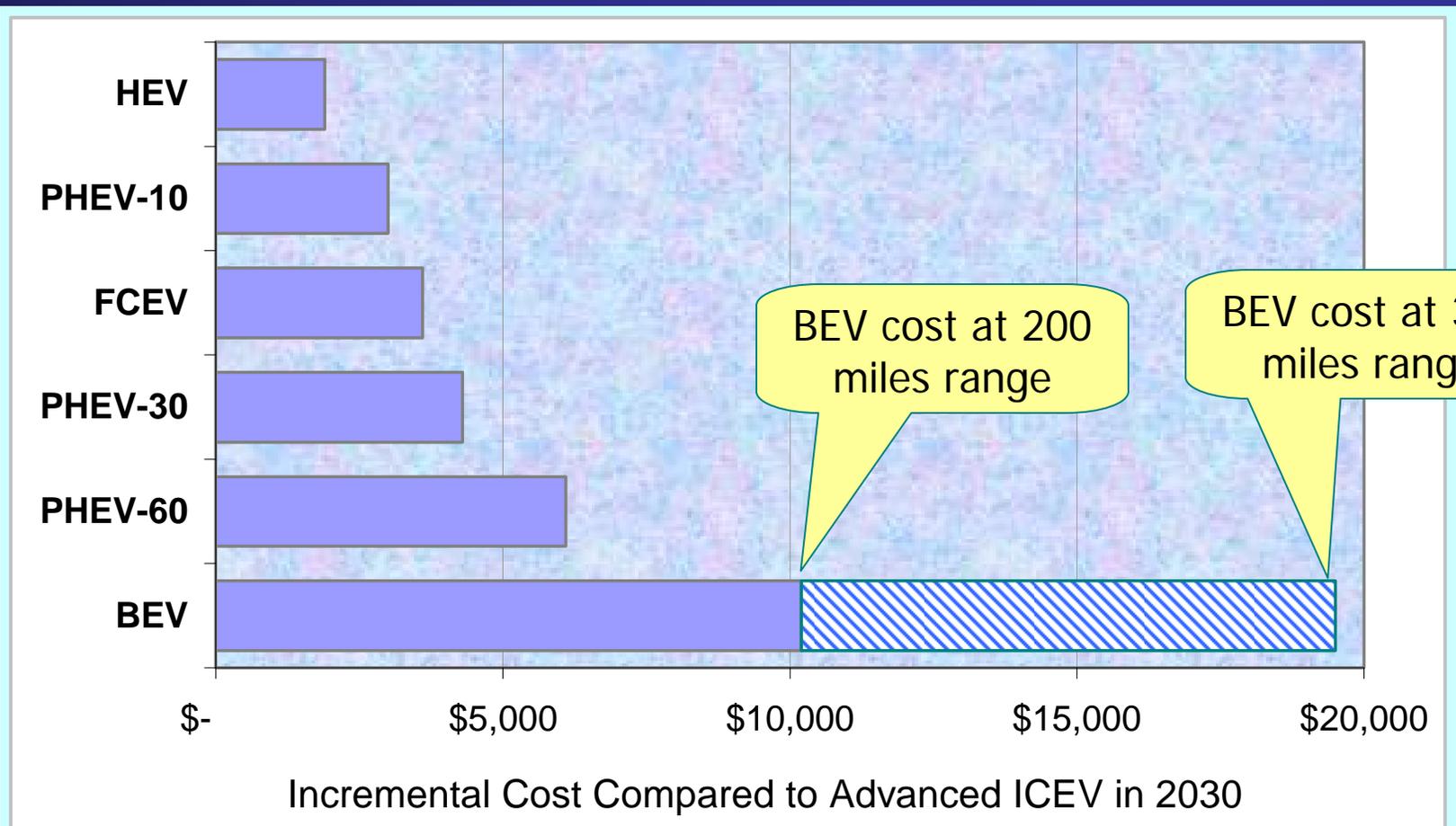
Ref: Kromer & Heywood, "Electric Powertrains: Opportunities & Challenges in the U.S. Light-Duty Vehicle Fleet
Report # LFEE 2007-03RP, MIT, May, 2007, Table 53

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



BEV cost estimate for 300 miles range

range (FCEV still at 350 miles range)



Story Simultaneous.XLS; Tab 'AFV Cost'; N 51 3/15/2009



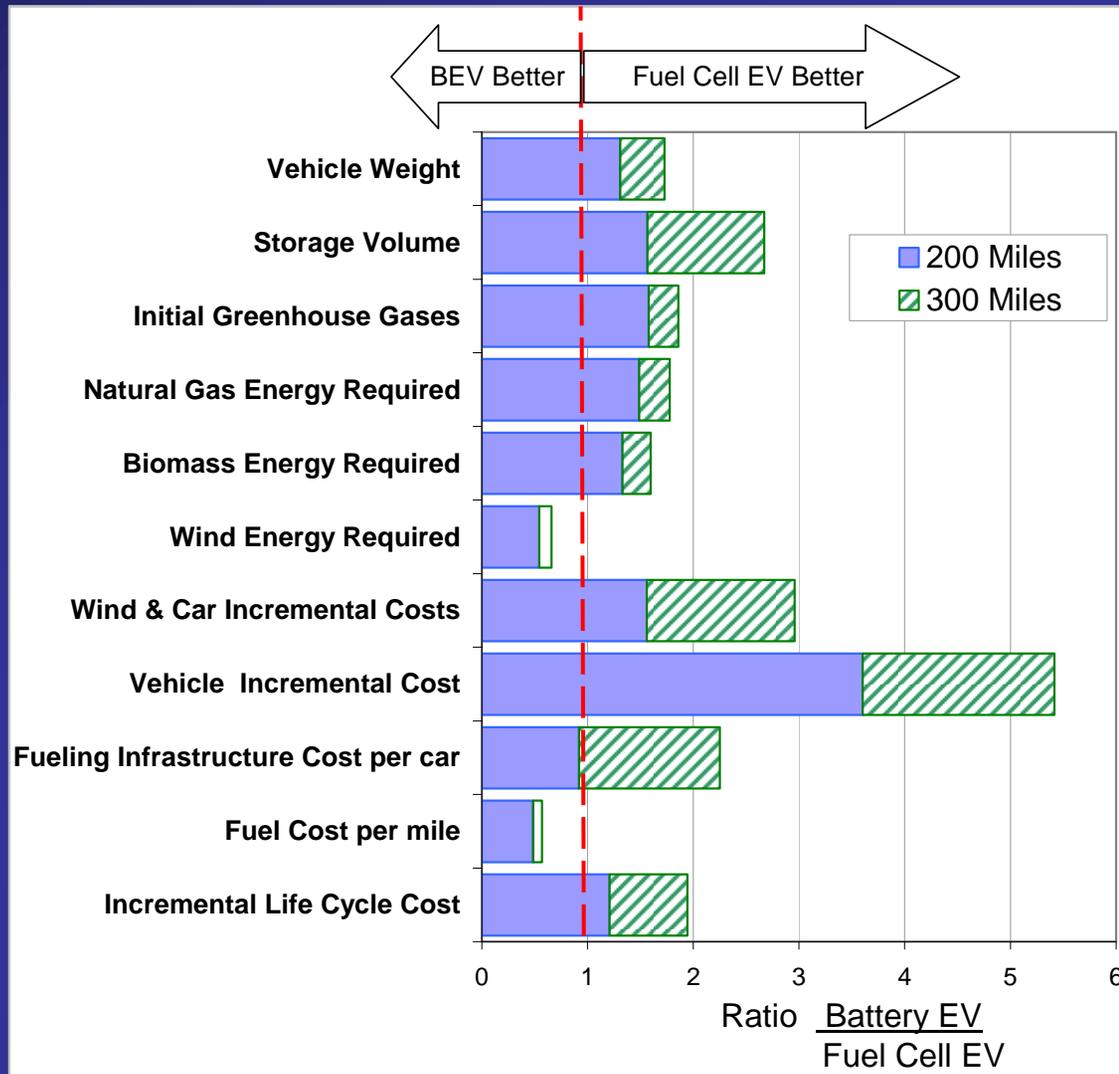
Comparison of MIT Cost Assumptions & DOE Goals

		DOE	DOE	MIT
		2010	2015	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



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%

Composite Comparison Chart

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Life Cycle Cost	83.1%	83.1%	100.8%	82.0%

Composite Comparison Chart

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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%

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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%

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%

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]*

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

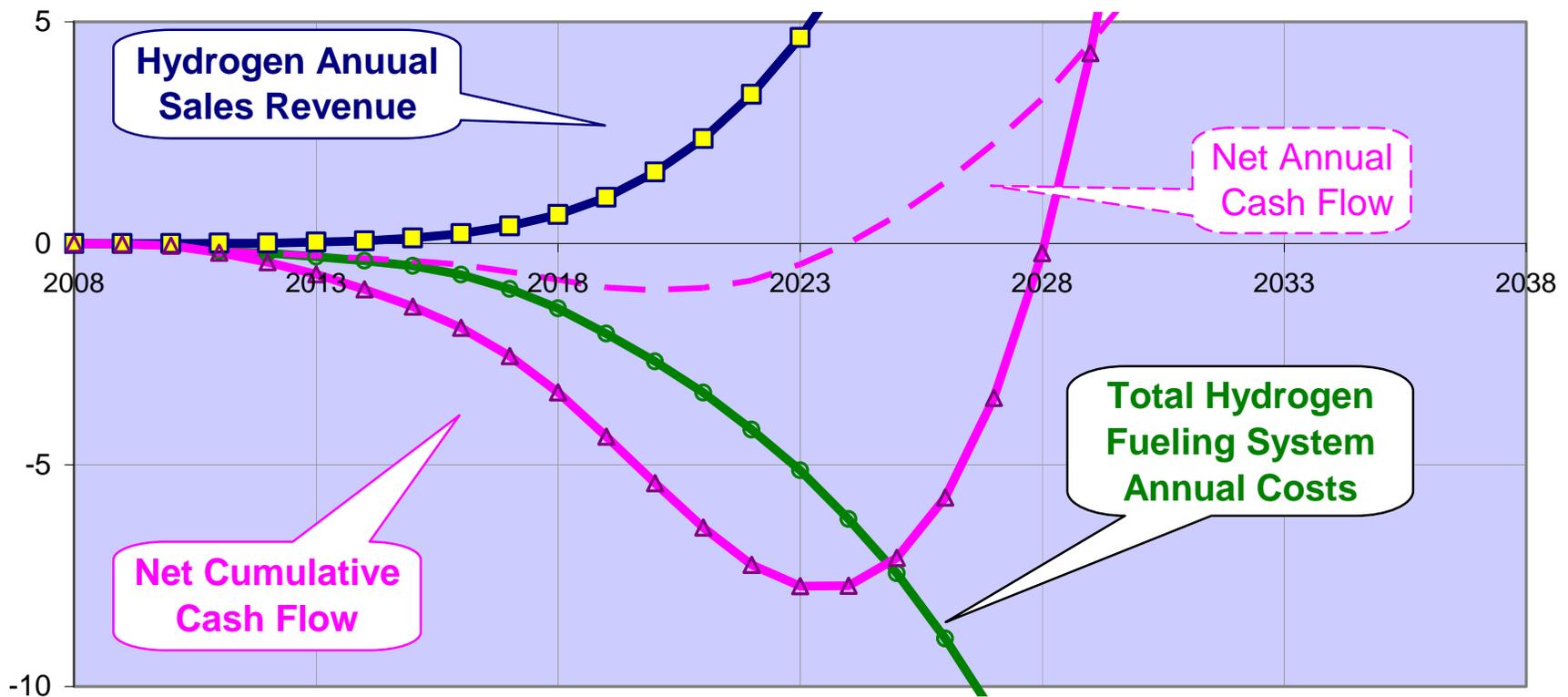
H2 Energy Story.XLS; Tab 'Annual Sales'; EC 18 5/15 /2009

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



Hydrogen Fueling Industry

Cash Flows for all Hydrogen Fueling Stations
(\$US Billions/year)



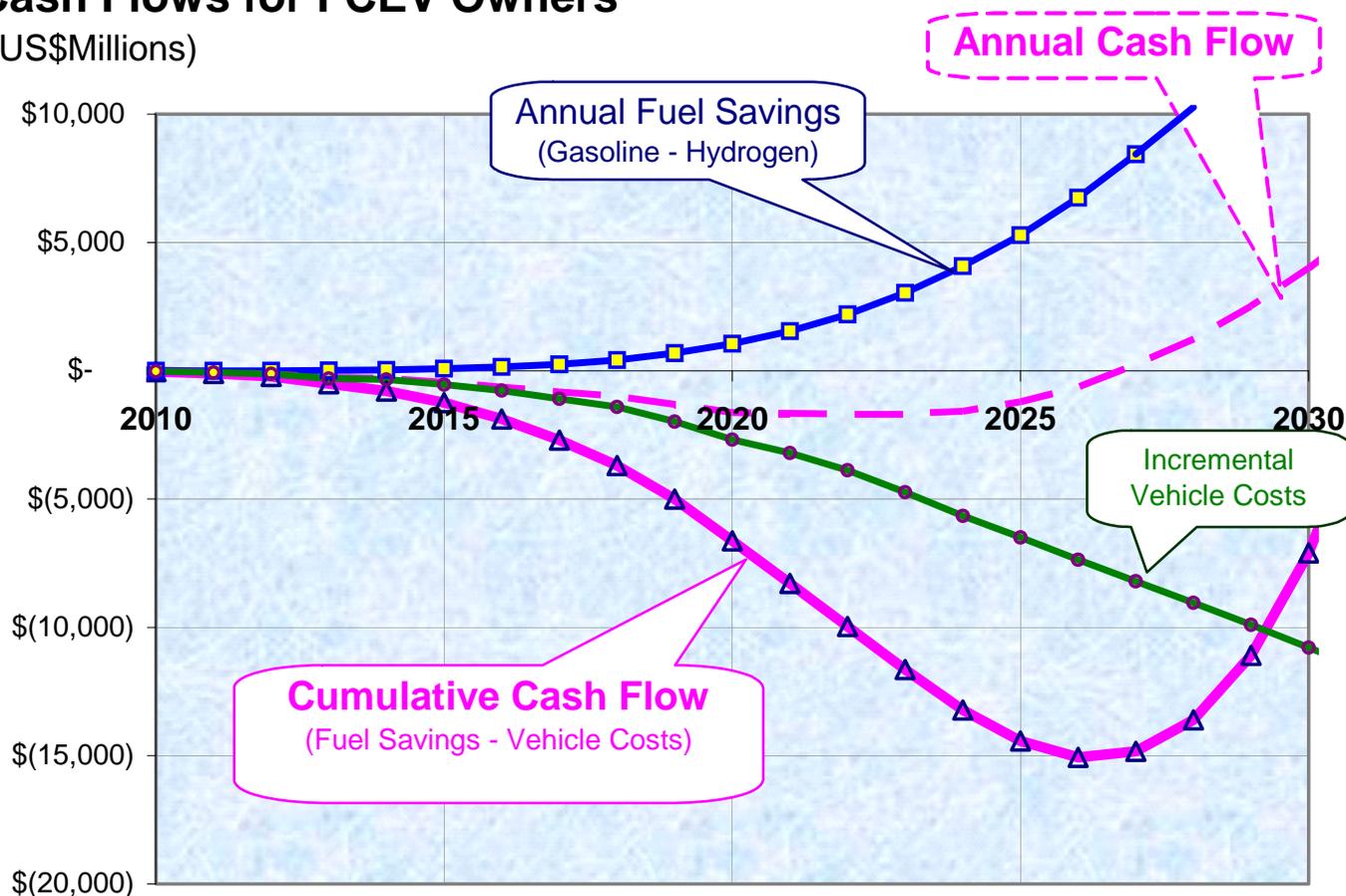
Hydrogen Price set at 55% of gasoline price per mile

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

Fuel Cell Vehicle Owners

Cash Flows for FCEV Owners

(US\$Millions)



*(Fuel Savings - Incremental

FCEV& BEV Premium Paid = \$ 1,000

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

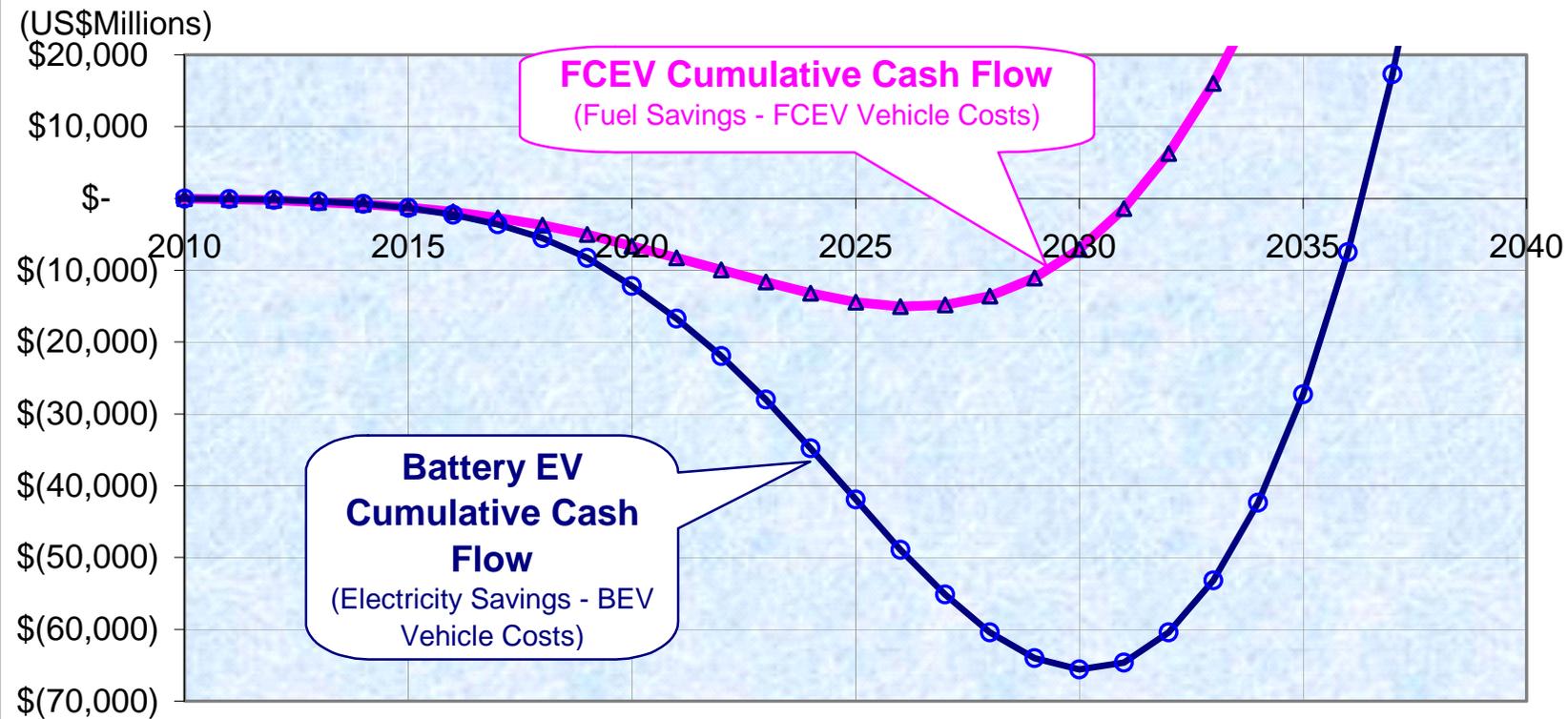
Fuel Savings Derating Factor = 0.80

H2 Price as fraction of gasoline price: 55%

Incentives Required for Battery EVs and Fuel Cell EVs



Cumulative Cash Flows for FCEV and Battery EV Owners

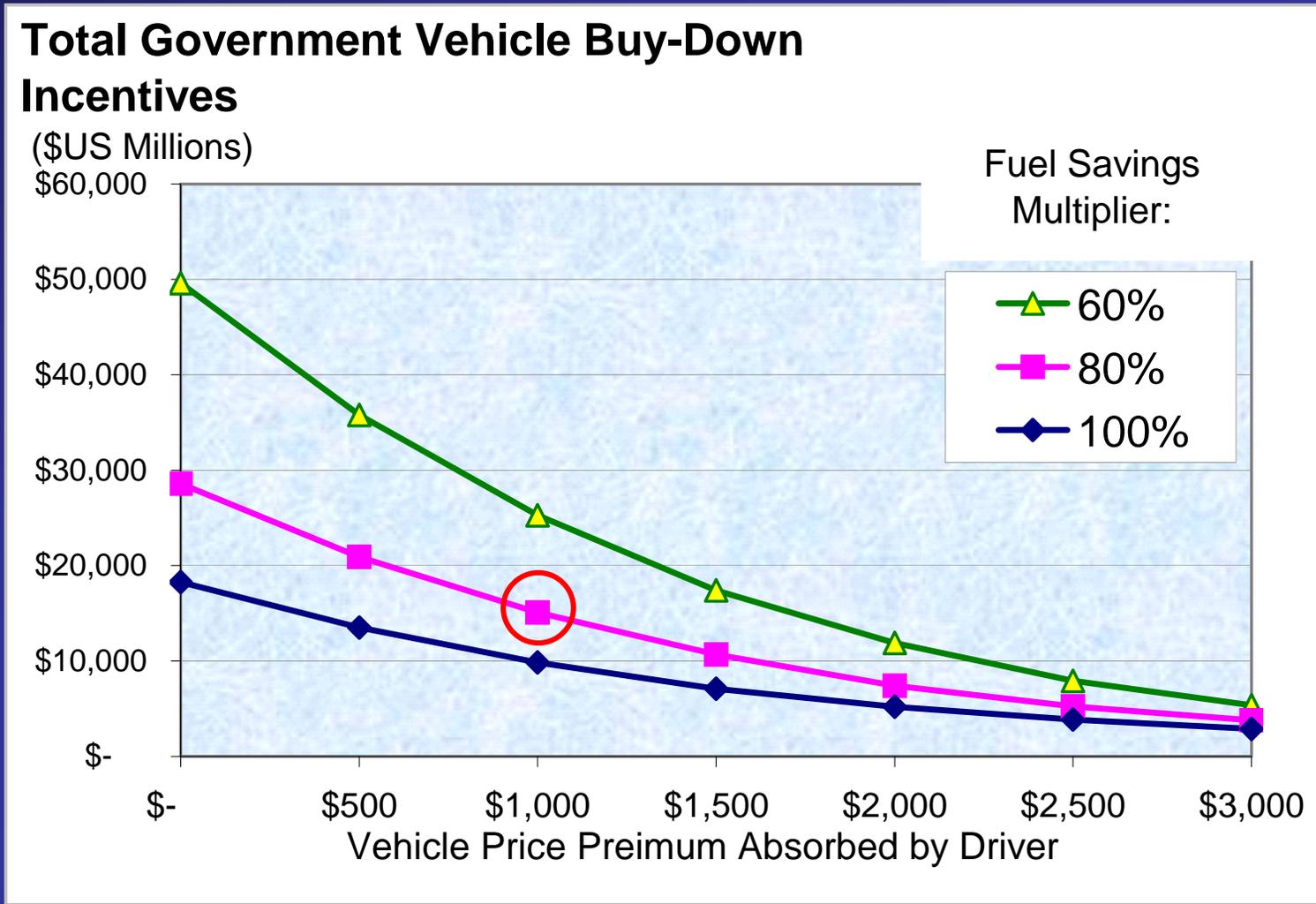


Vehicle Premium: \$ 1,000
Fuel Fraction 0.80

Off-Peak Electricity (% of On-Peak) = 55%
H2 Price (% of Gasoline per mile) = 55%

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

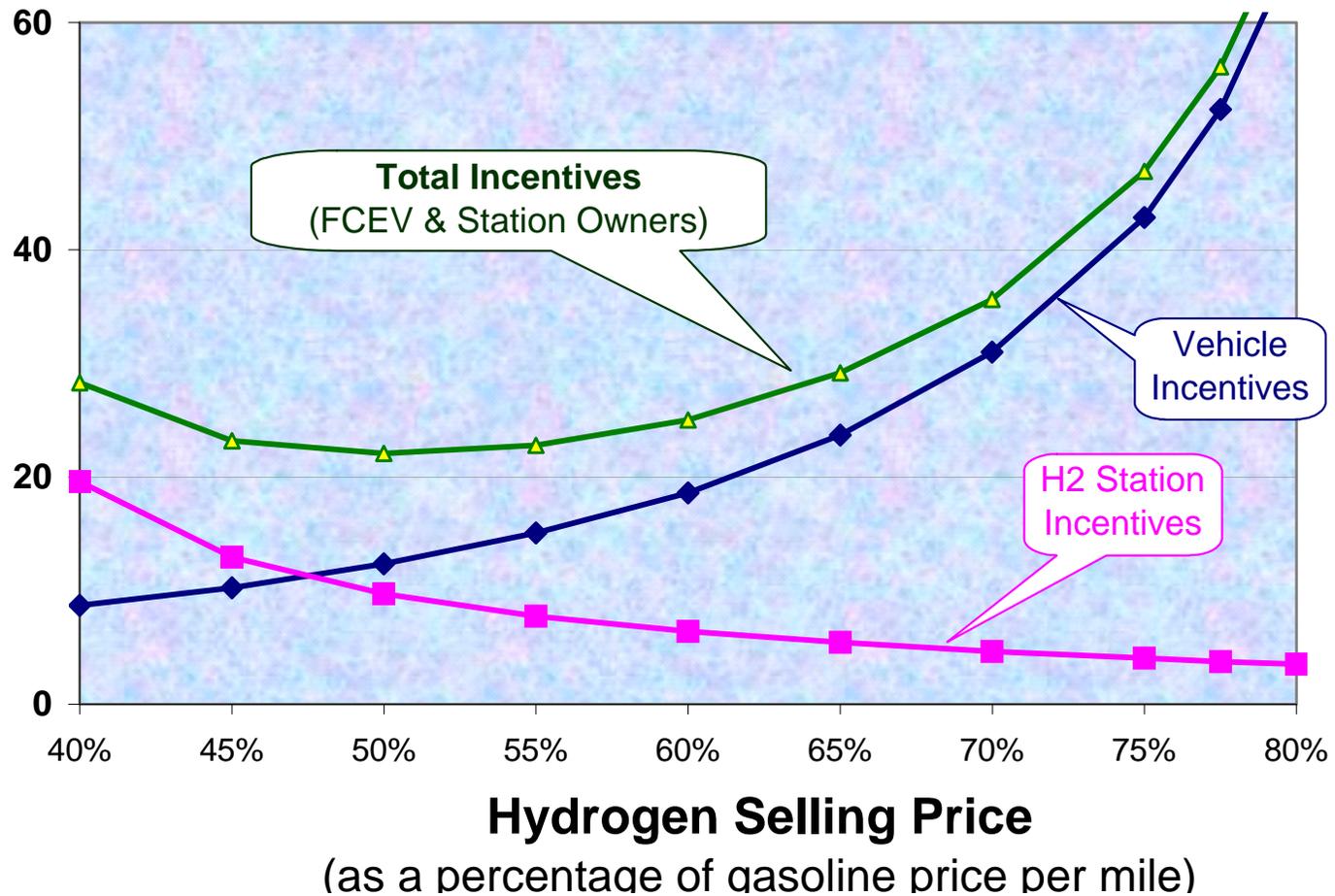
Vehicle Buy-Down Incentives Required



Incentives Required

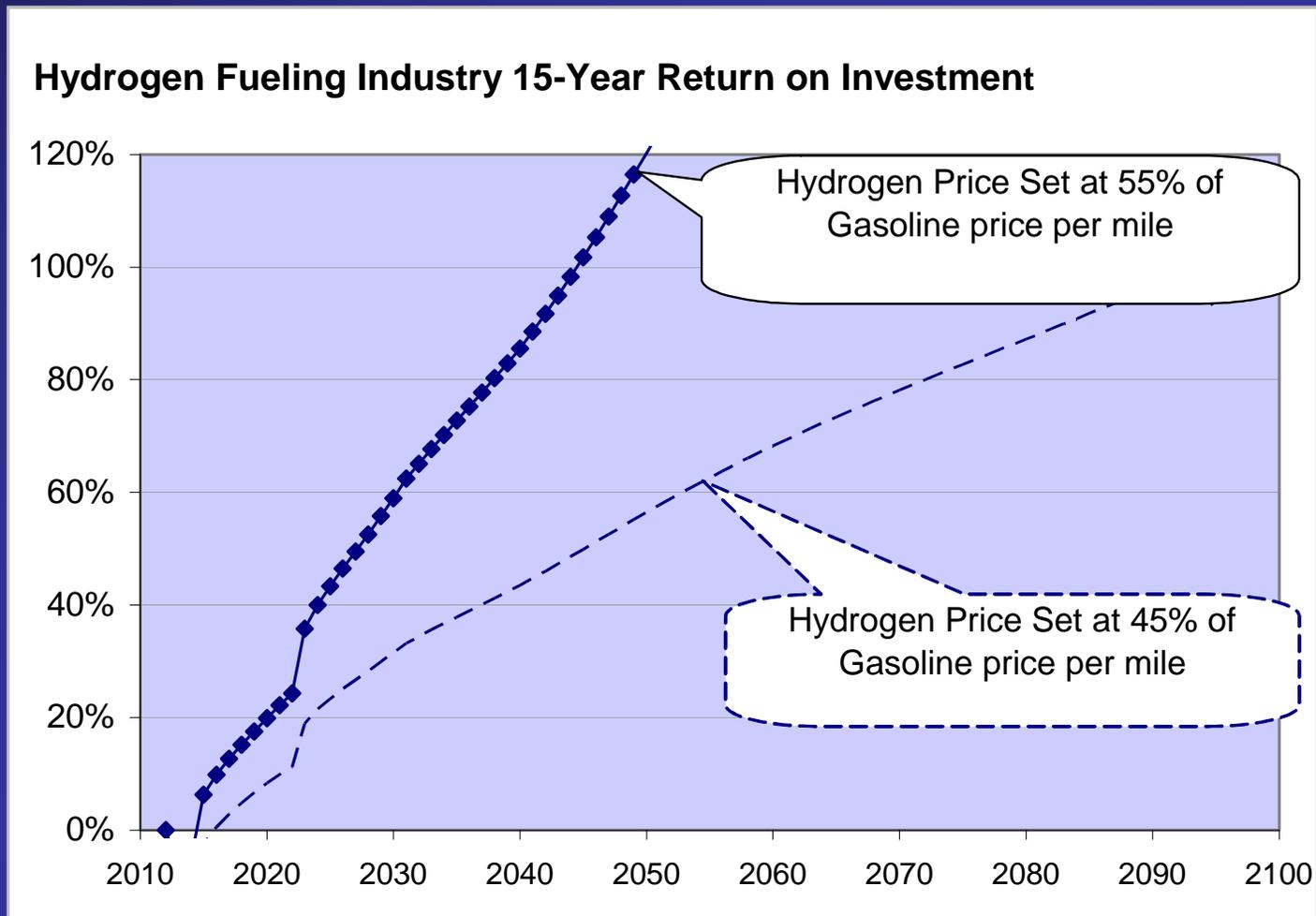
Incentives Required

(US\$ Billions)



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

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



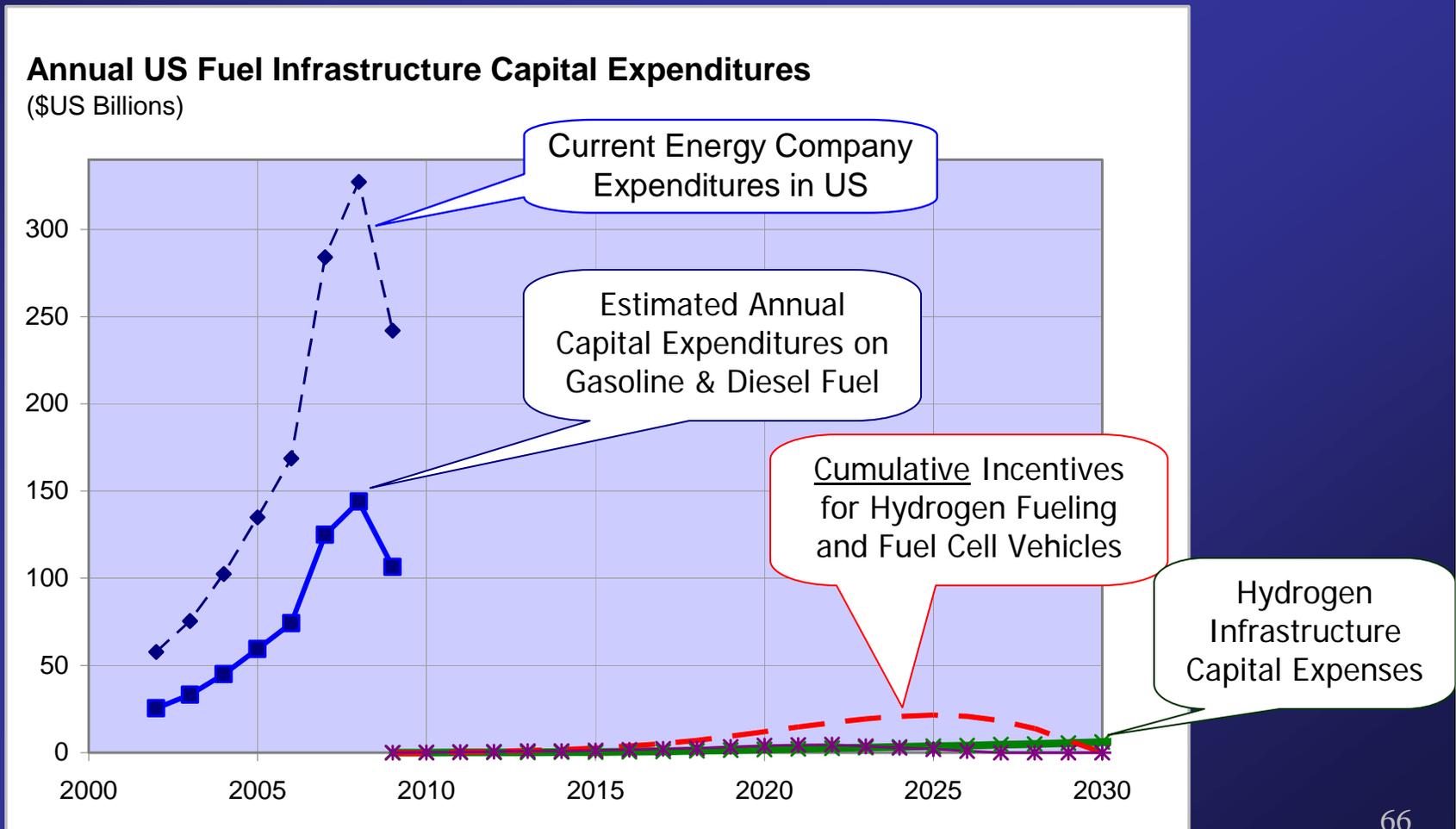


Net Cumulative Incentives Required

- 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

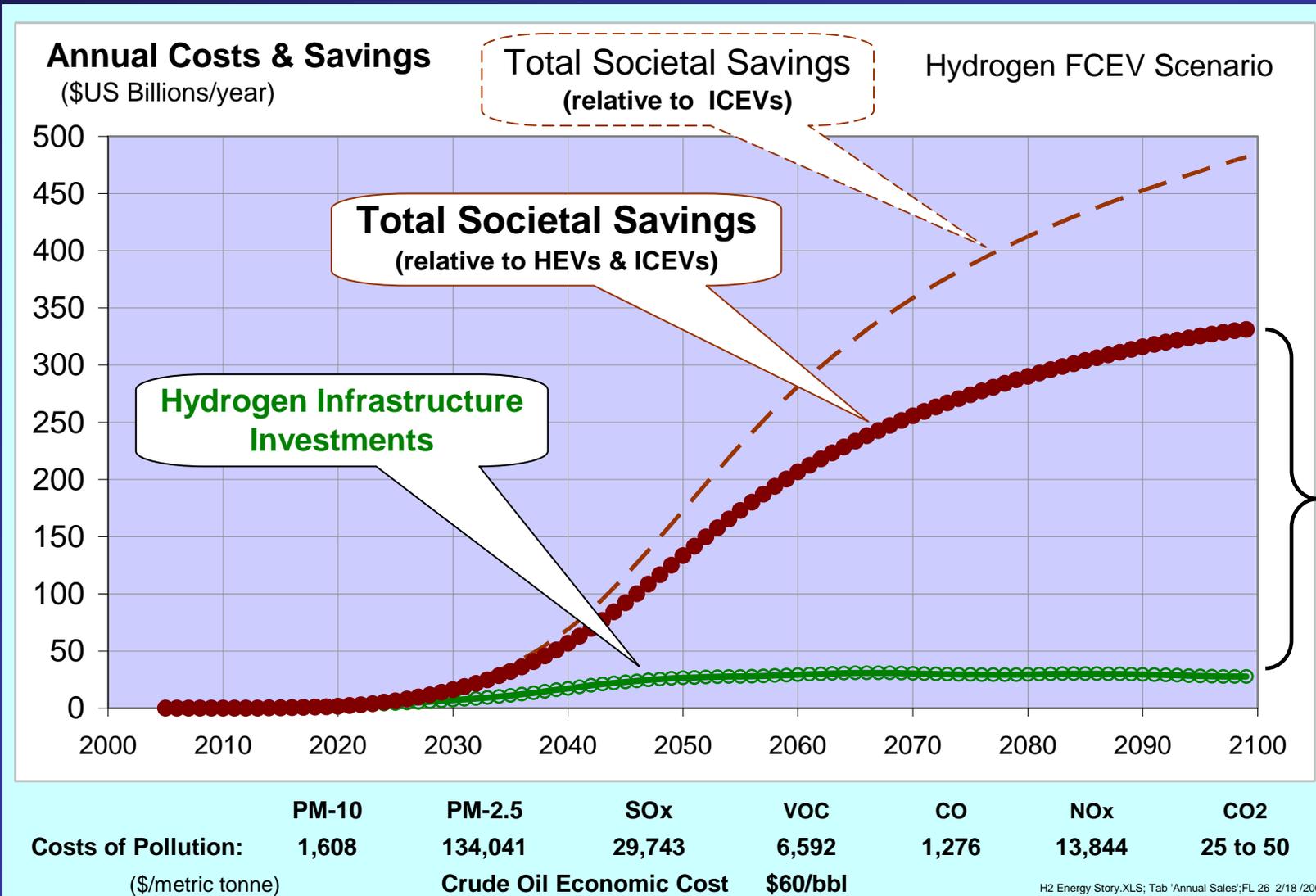
(Compared to Gasoline & Diesel Infrastructure Costs)



Source: Oil & Gas Journal, April 2009

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

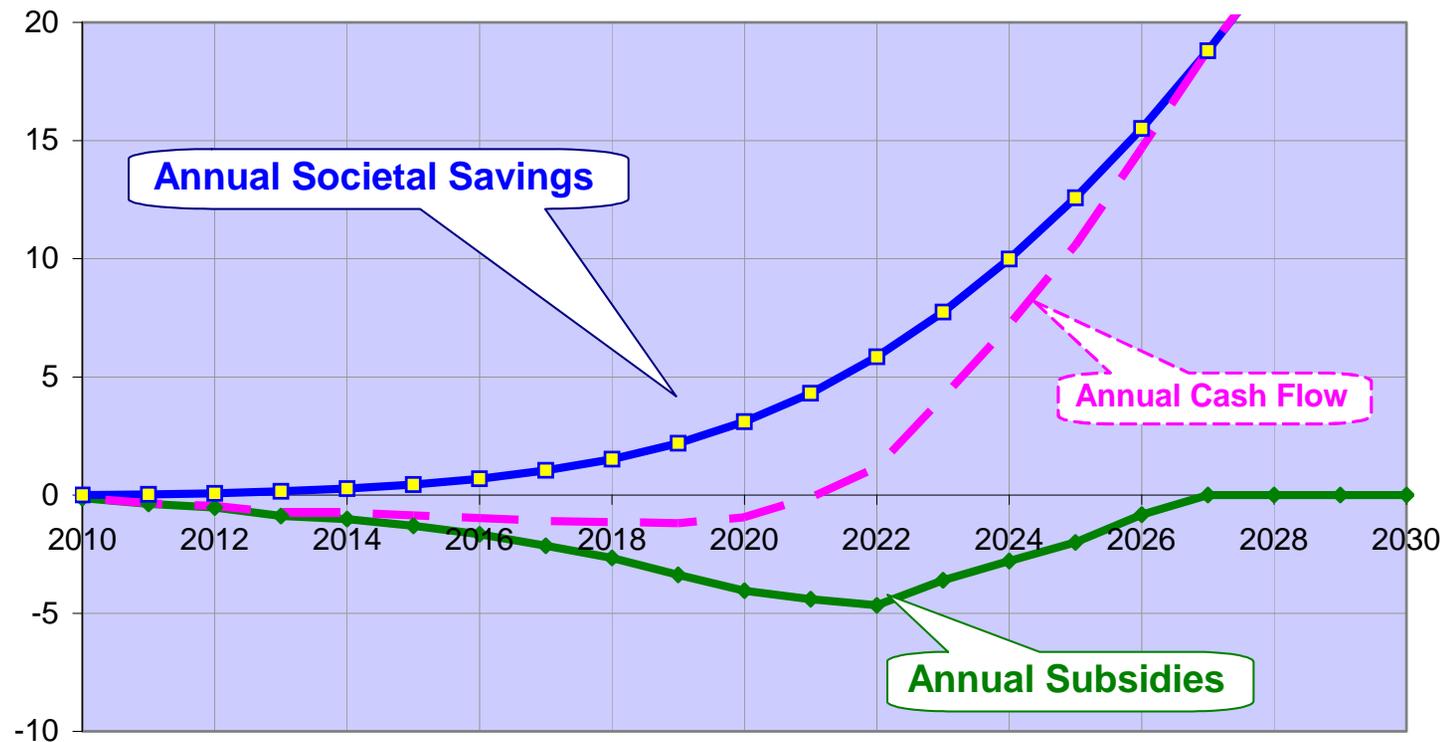
H₂ Costs & Societal Savings



Societal Cash Flow

Annual Cash Flow
(\$US Billions)

Fuel Cell Electric Vehicle Scenario*
(Societal Savings - Government Subsidies)

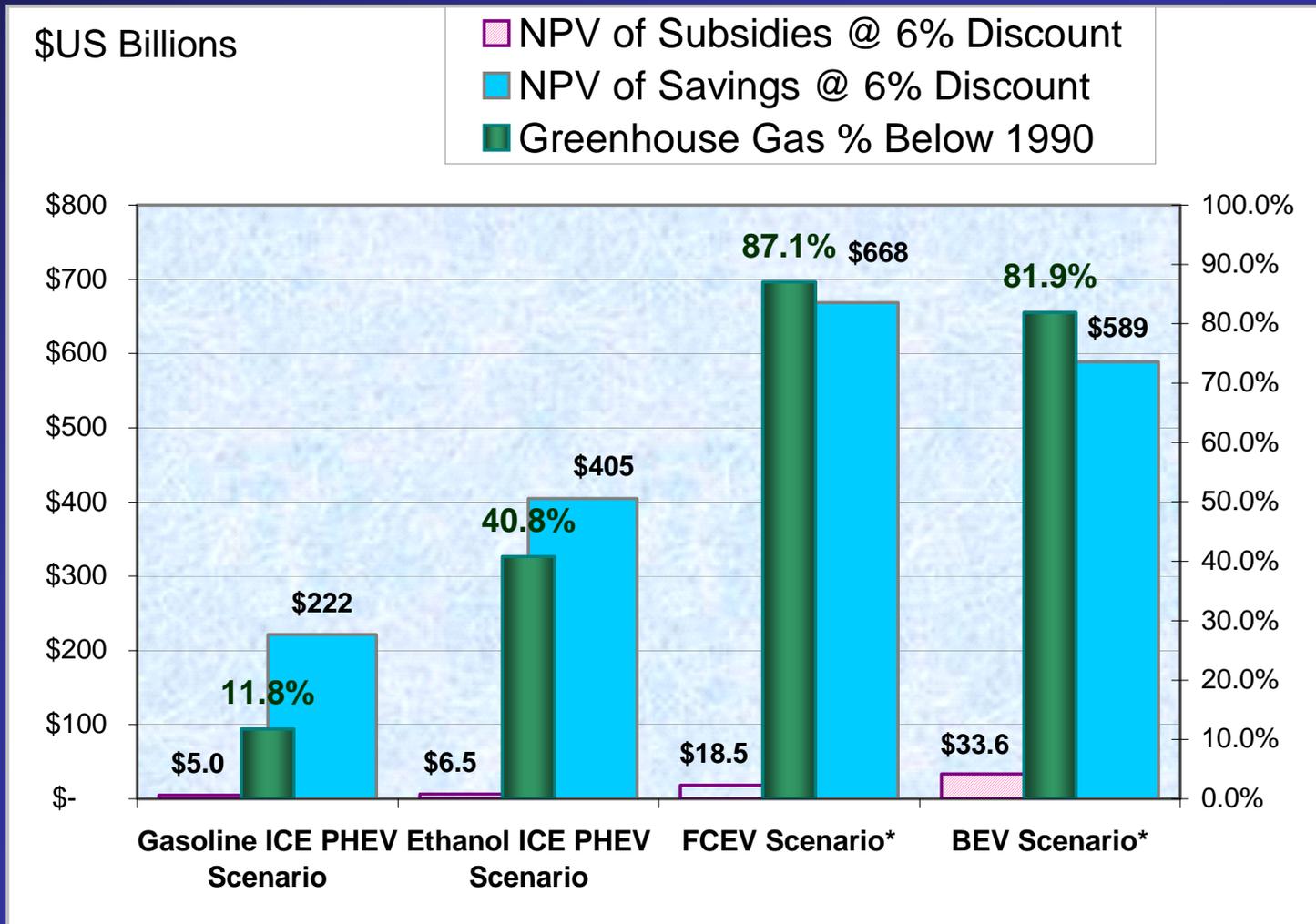


* Costs and savings include those for the PHEVs

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



* 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

H₂Gen





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

1. Ramage, M P, Chair, Committee on the Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, “Transitions to Alternative Transportation Technologies—A Focus on Hydrogen,” National Research Council of the National Academies, Washington, DC, 2008 http://books.nap.edu/catalog.php?record_id=12222#toc
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/](http://www.transportation.anl.gov/software/GREET/)
6. Dhameja S., *Electric Vehicle Battery Systems*, Newnes Press, Boston 2002
7. Wipke K, S.Sprick, 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

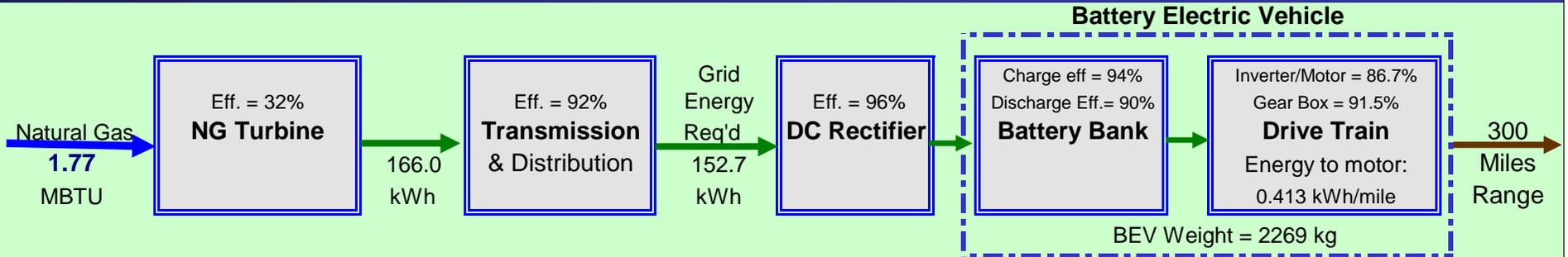
Thank You

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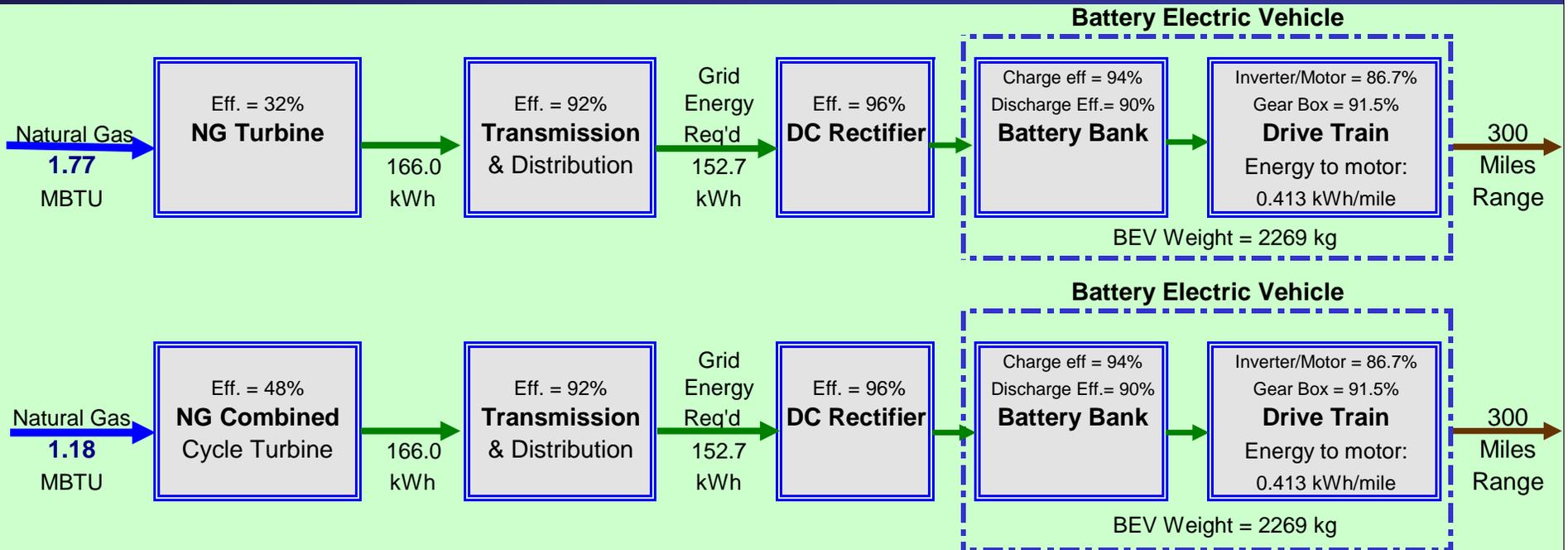


Backup Slides

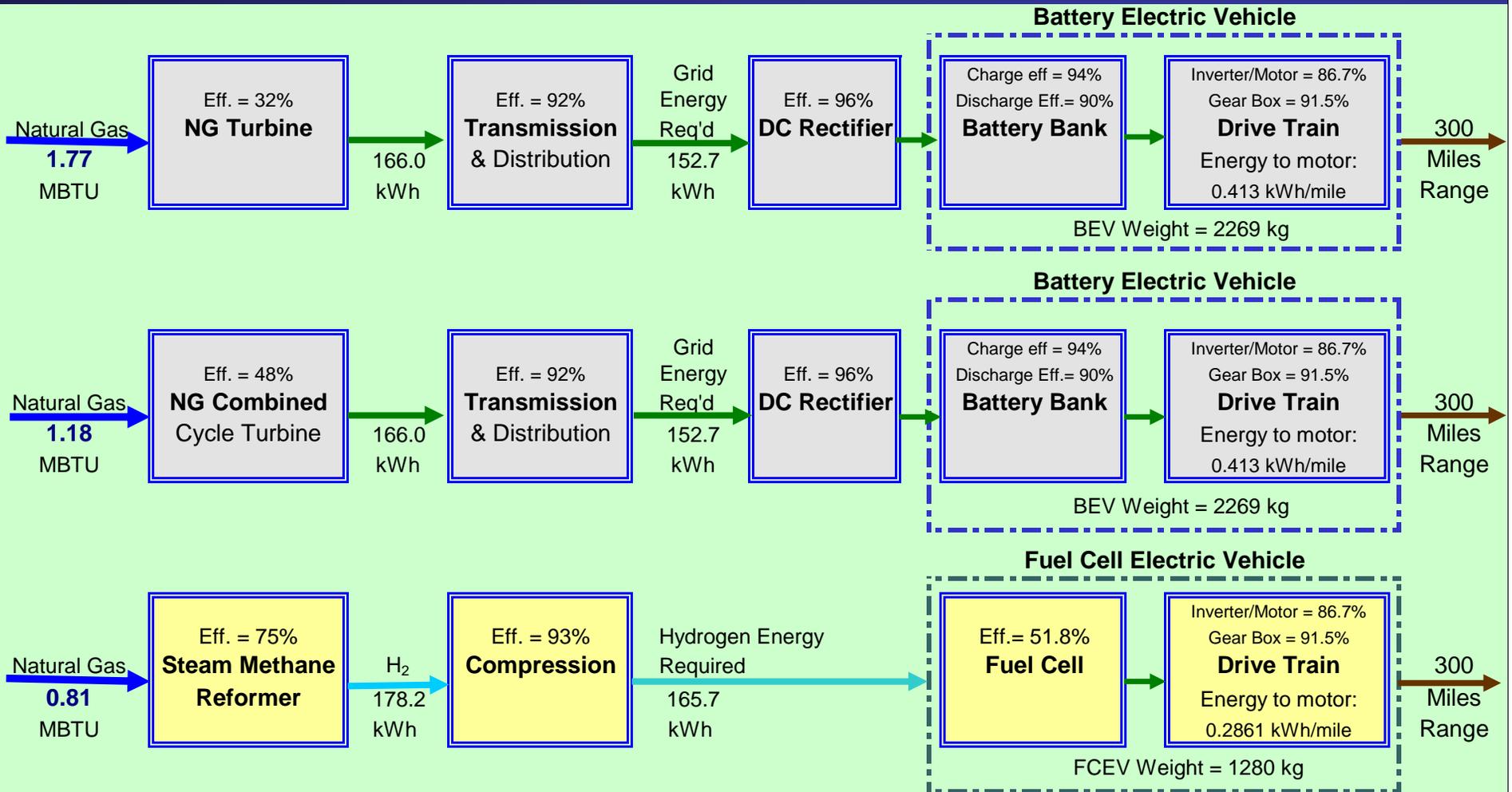
Natural Gas: Battery EVs via Electricity? **H₂Gen** Or Fuel Cell EVs via Hydrogen?



Natural Gas: Battery EVs via Electricity? **H₂Gen** Or Fuel Cell EVs via Hydrogen?



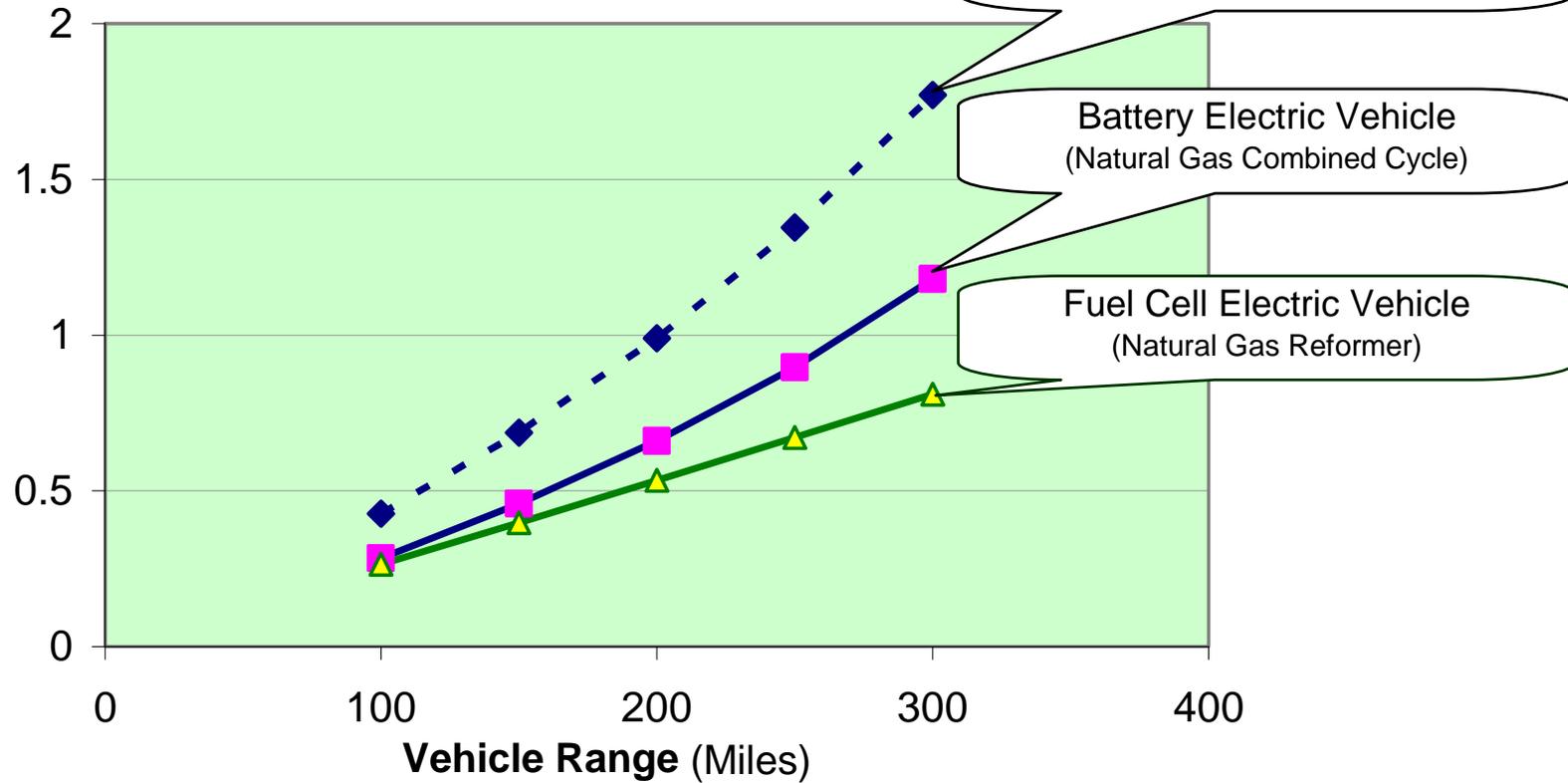
Natural Gas: Battery EVs via Electricity? **H₂Gen** Or Fuel Cell EVs via Hydrogen?



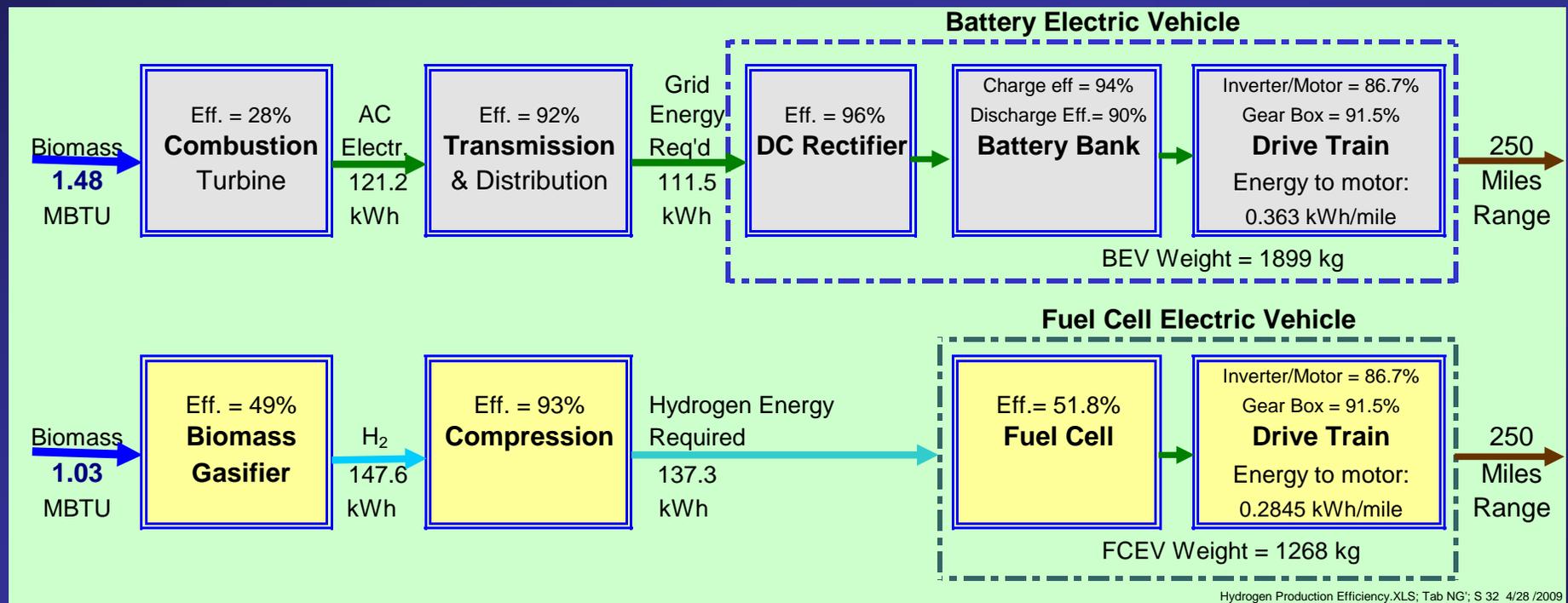
Hydrogen Production Efficiency.XLS; Tab NG; S 44 3/12/2009

Natural Gas Required for Electric Vehicles

Natural Gas Required (MBTU)



Biomass Utilization: BEV or FCEV?

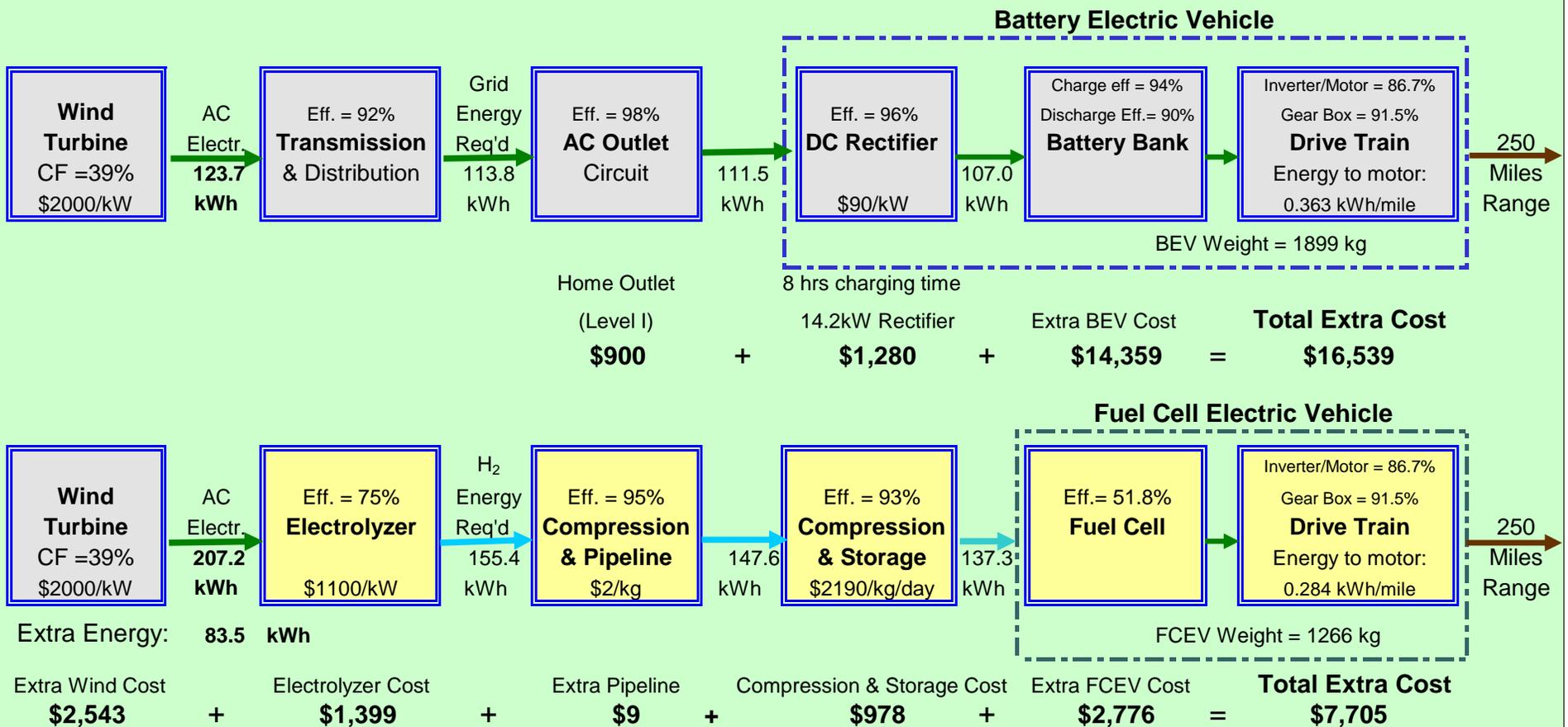


Biomass to electricity reference: Duvall, M., Khipping, E., "Environmental assessment of PHEVs Vol 1 – National greenhouse gas emissions," EPRI/NRDC Rept # 1015325, July 2007

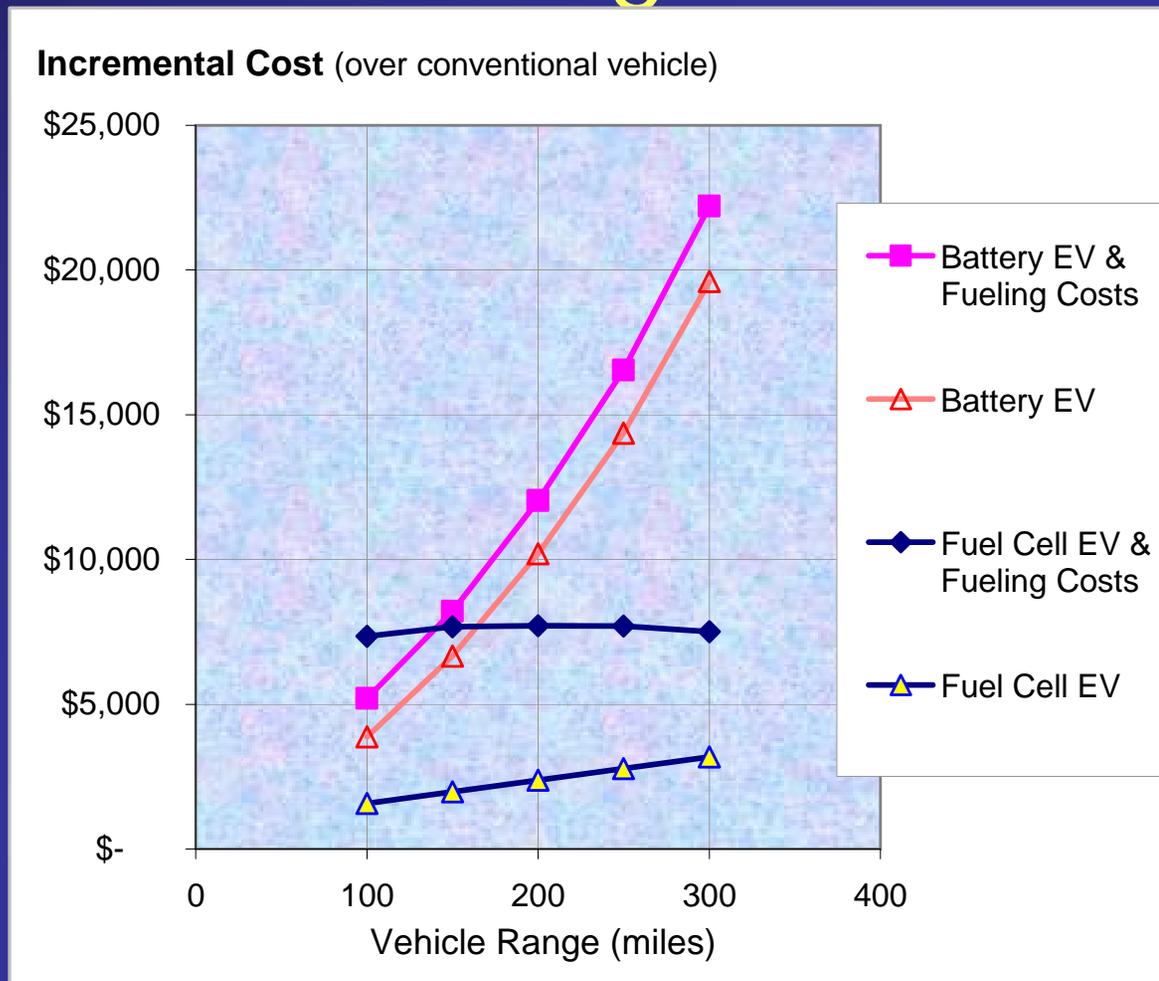
Biomass to hydrogen: Spath, P, Aden A, Eggeman T, Ringer M, Wallace B, Jechura J, "Biomass to hydrogen production detailed design and economics," NREL/TP-510-37408, May 2005

Vehicle parameters: 2.13 m² area, 0.33 drag, 0.0092 rolling resistance & 0 to 60 mph acceleration in 10 seconds

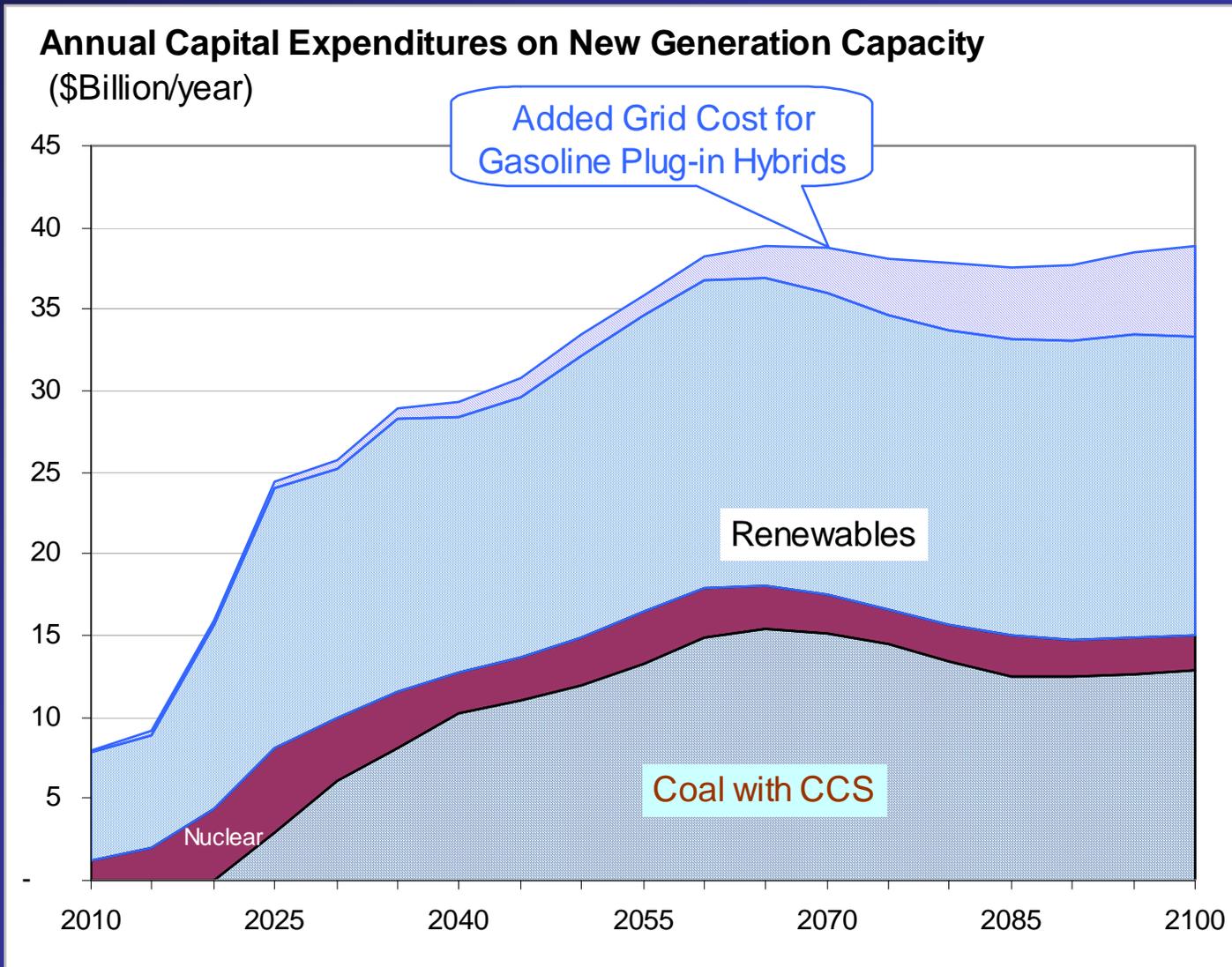
Wind Electricity: BEV or FCEV?



Incremental Cost: Vehicle + Fueling Costs

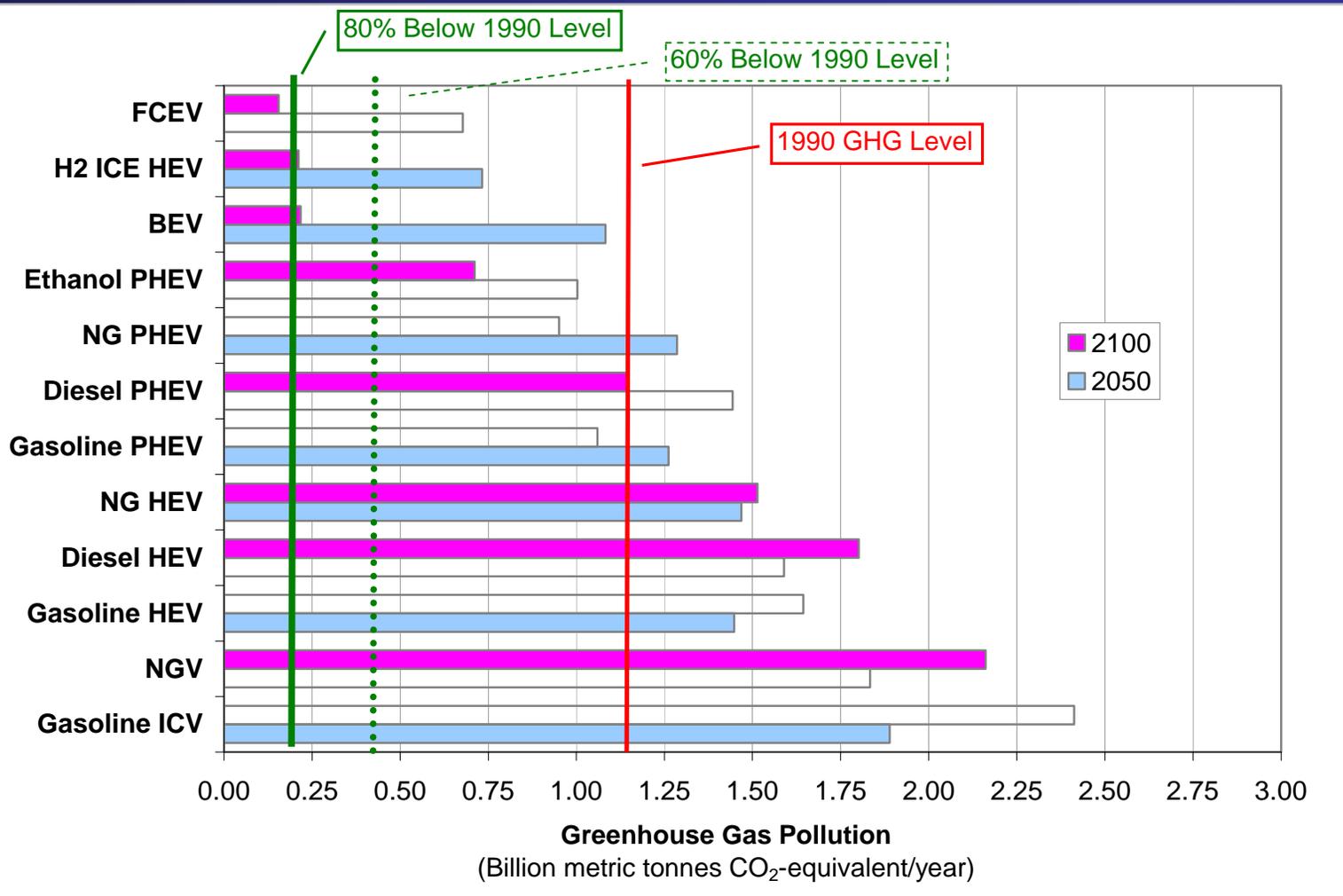


Cost to Reduce Grid Carbon Footprint **H₂Gen**



Source: EPRI for generator capital costs and capacity factors

Greenhouse Gas Pollution Comparisons (2050 & 2100)

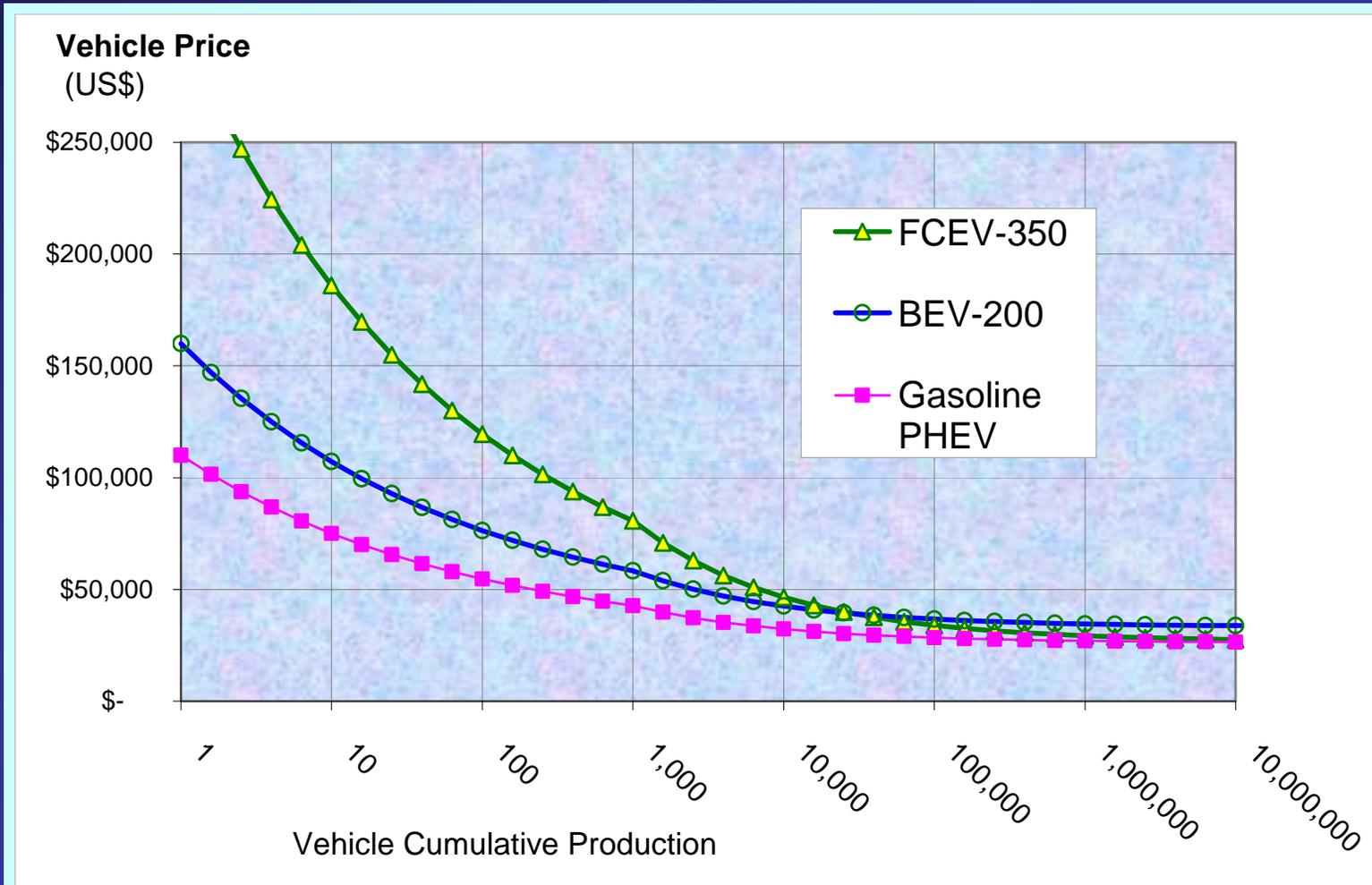


GHG = greenhouse gases
 FCEV = fuel cell hybrid electric vehicle
 HEV = hybrid electric vehicle
 PHEV = plug-in hybrid electric vehicle
 NG = natural gas
 NGV = natural gas vehicle
 ICV = internal combustion engine vehicle

Based on AEO 2009 data

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

Vehicle Costs vs. Production Volume



	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

DOE FY2010 Budget Request



(\$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)
<i>Fuel Cell Stack Component R&D</i>	-	-	-	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	10,000,000	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.

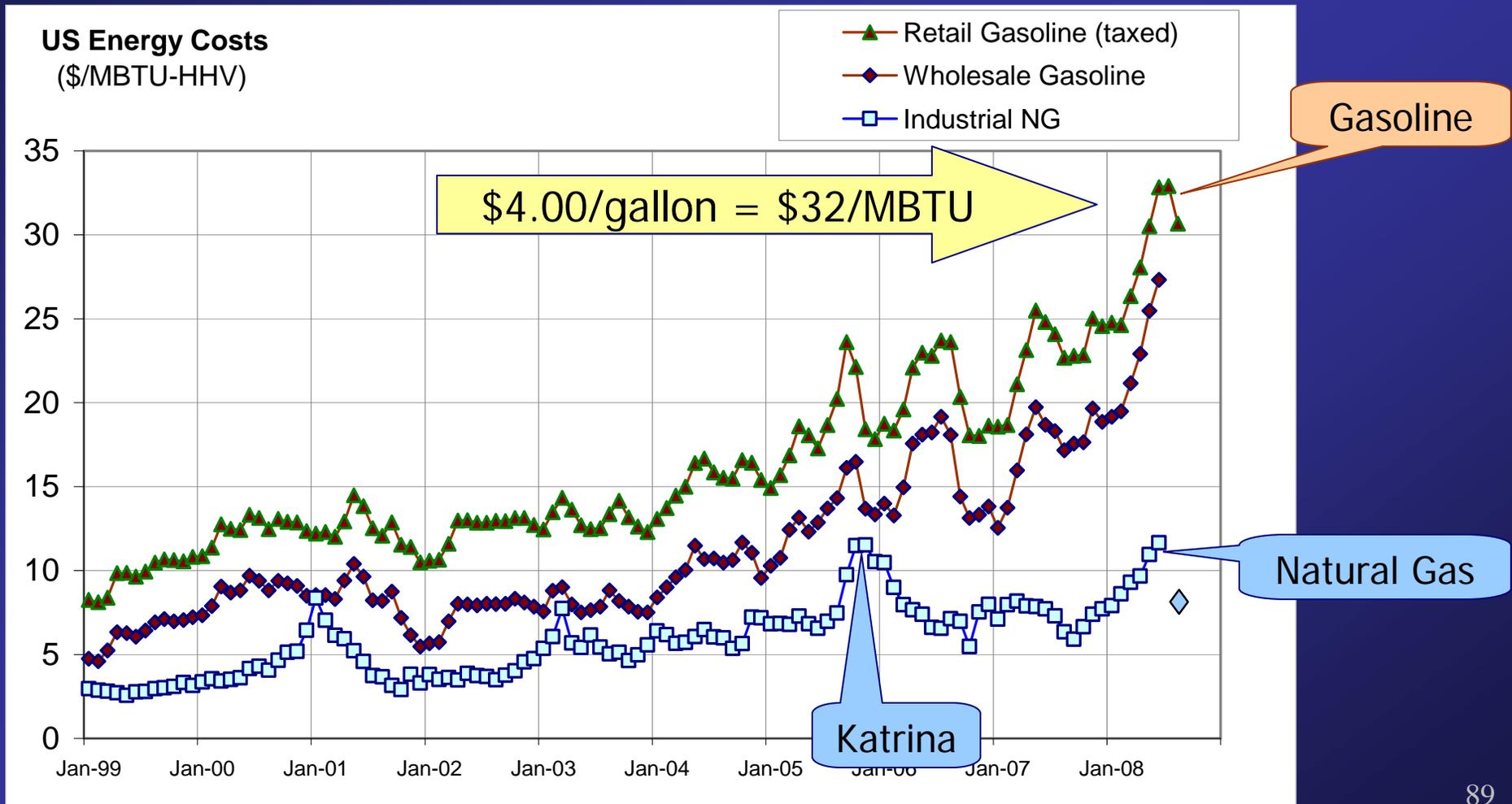
^b Facilities and Infrastructure includes \$13.5 million for the Integrated Biorefinery Research Facility, for a total of \$800 million in Biomass related Recovery funded projects.

^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."

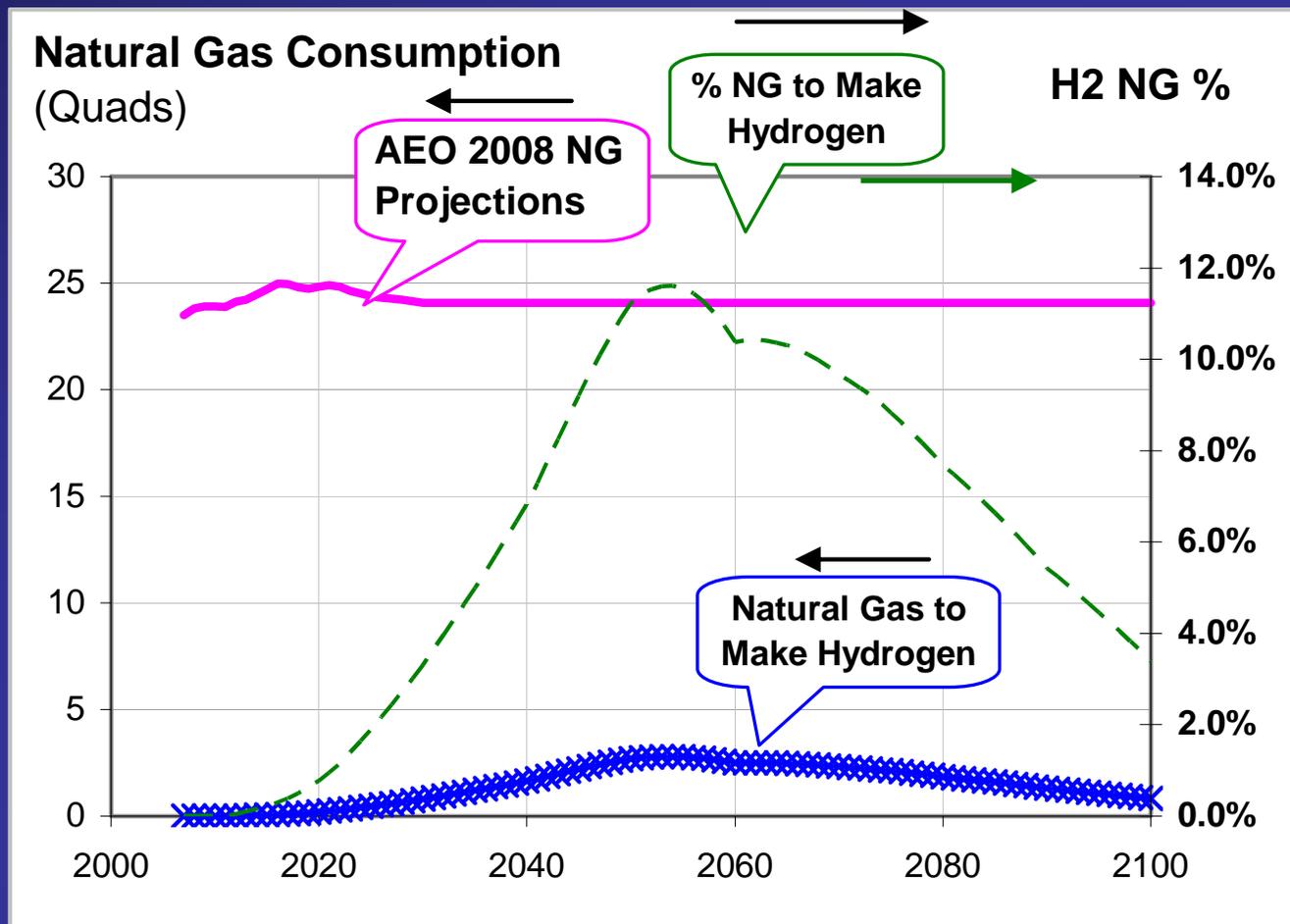
Energy Efficiency and Renewable Energy/
Overview

FY 2010 Congressional Budget

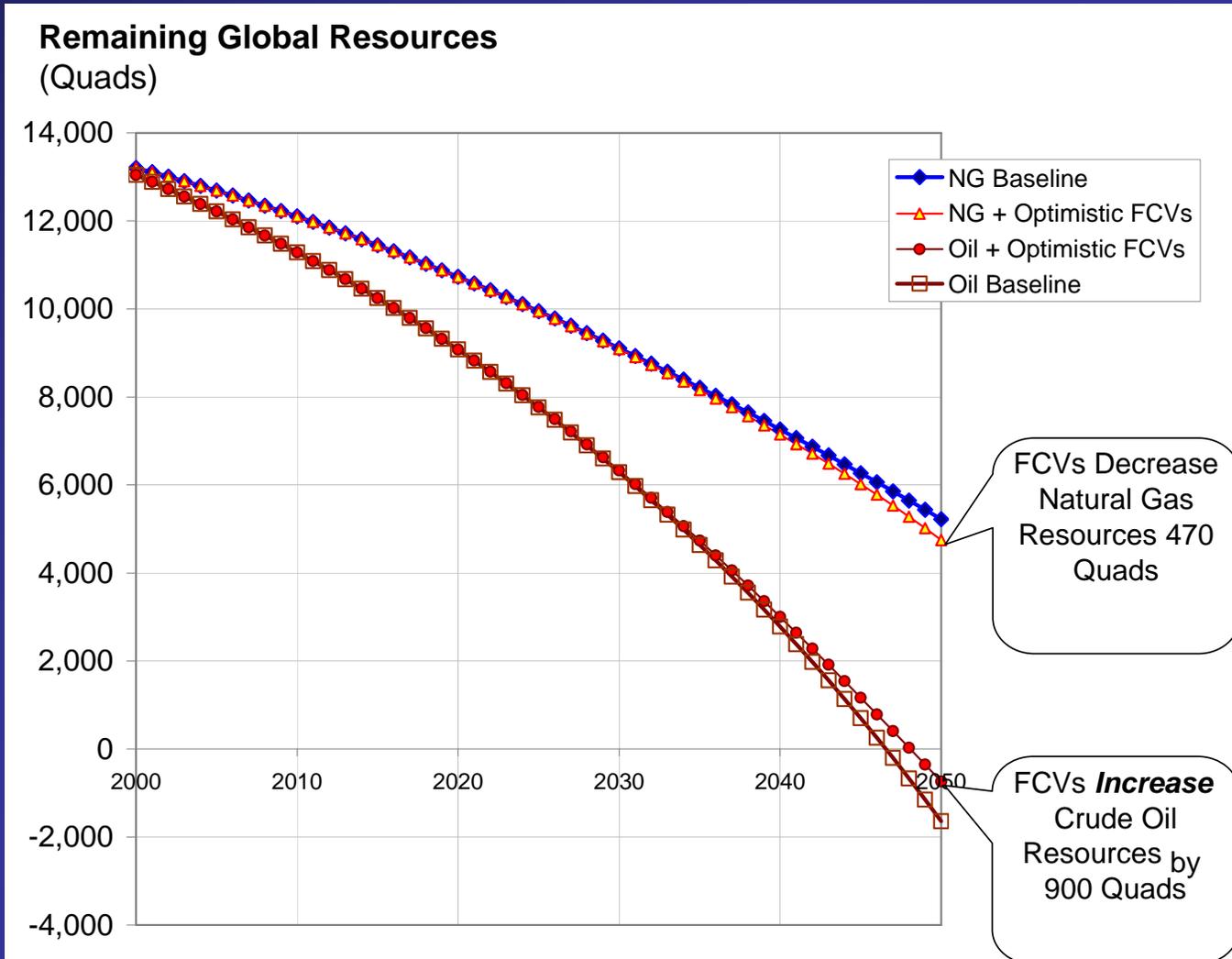
Natural Gas vs. Gasoline Prices



Natural Gas use for FCVs



Impact of FCVs on Global Natural Gas Resources



Marginal Grid Mix Illustration

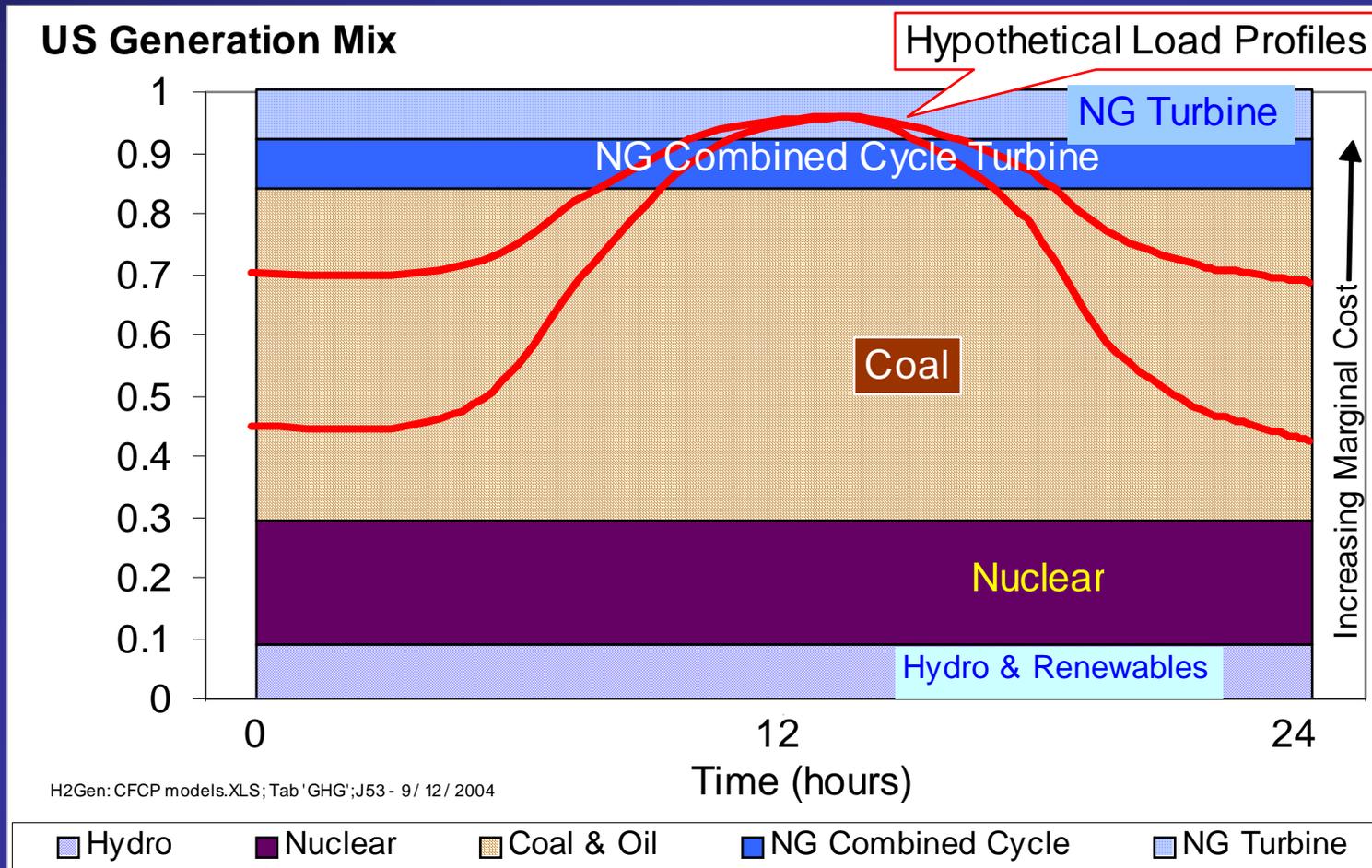


Figure . Illustration of marginal grid loads for a typical US electric utility

Societal Cost / Benefit Results

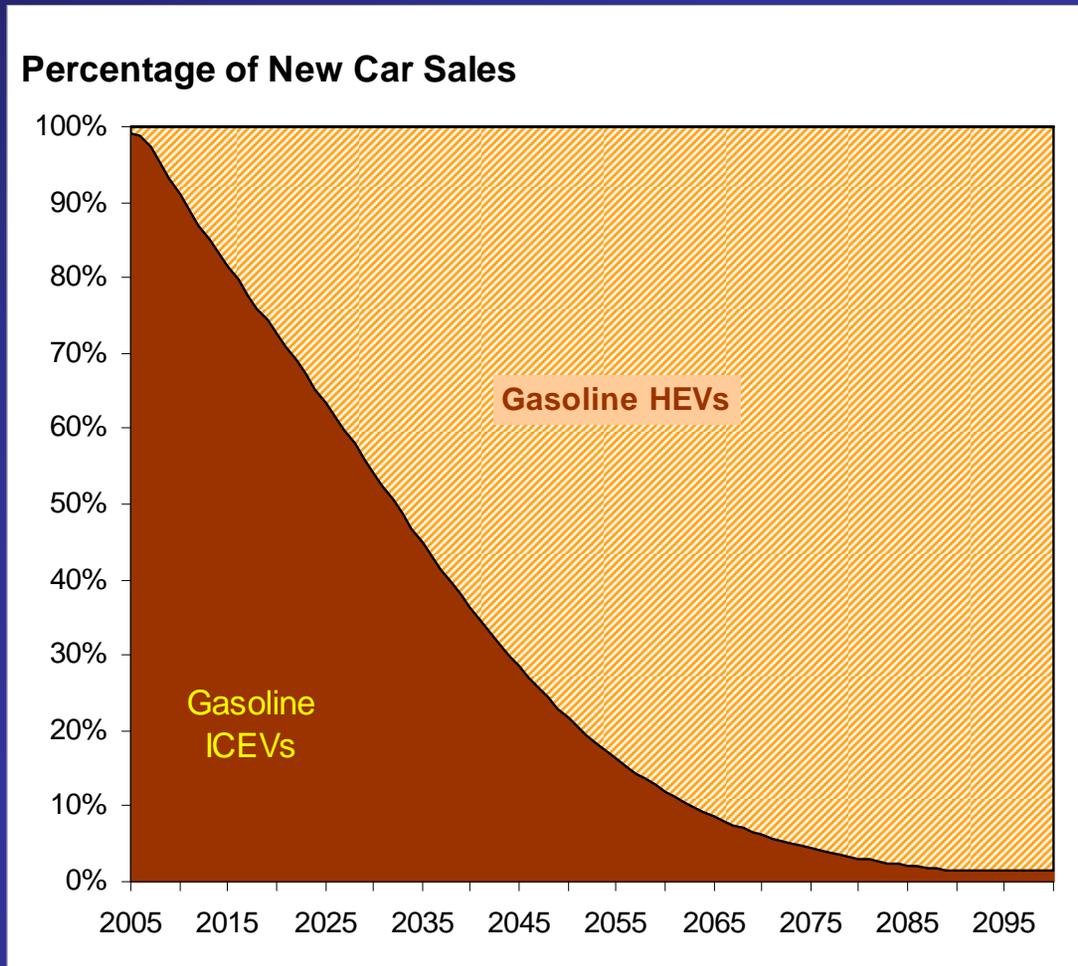
	Gasoline ICE PHEV Scenario	Ethanol ICE PHEV Scenario	FCEV Scenario*	BEV Scenario*
Total Subsidies & Investments (\$US Billions)	\$ 8.6	\$ 12.4	\$ 36.5	\$ 79.2
Total Societal Savings (\$US Billions)	\$ 5,635	\$ 9,565	\$ 15,863	\$ 15,293
Ratio of Savings / Subsidies	653	769	435	193
Discount Rate = 6%				
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

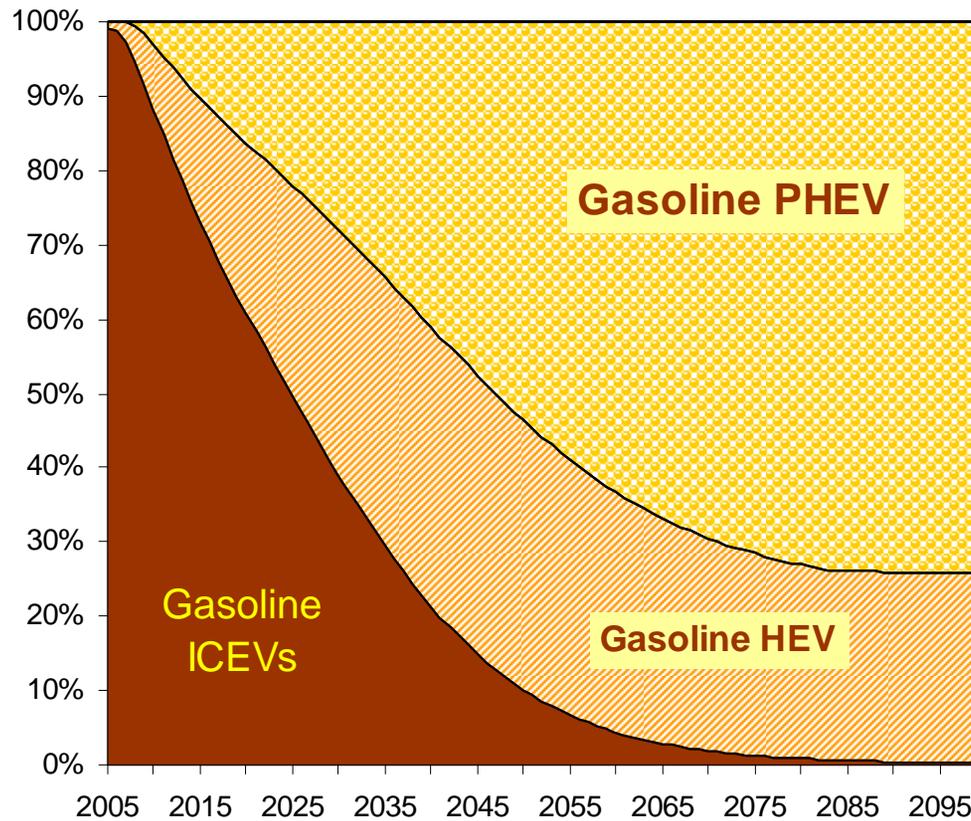


(50% Market Share Potential by 2024)

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

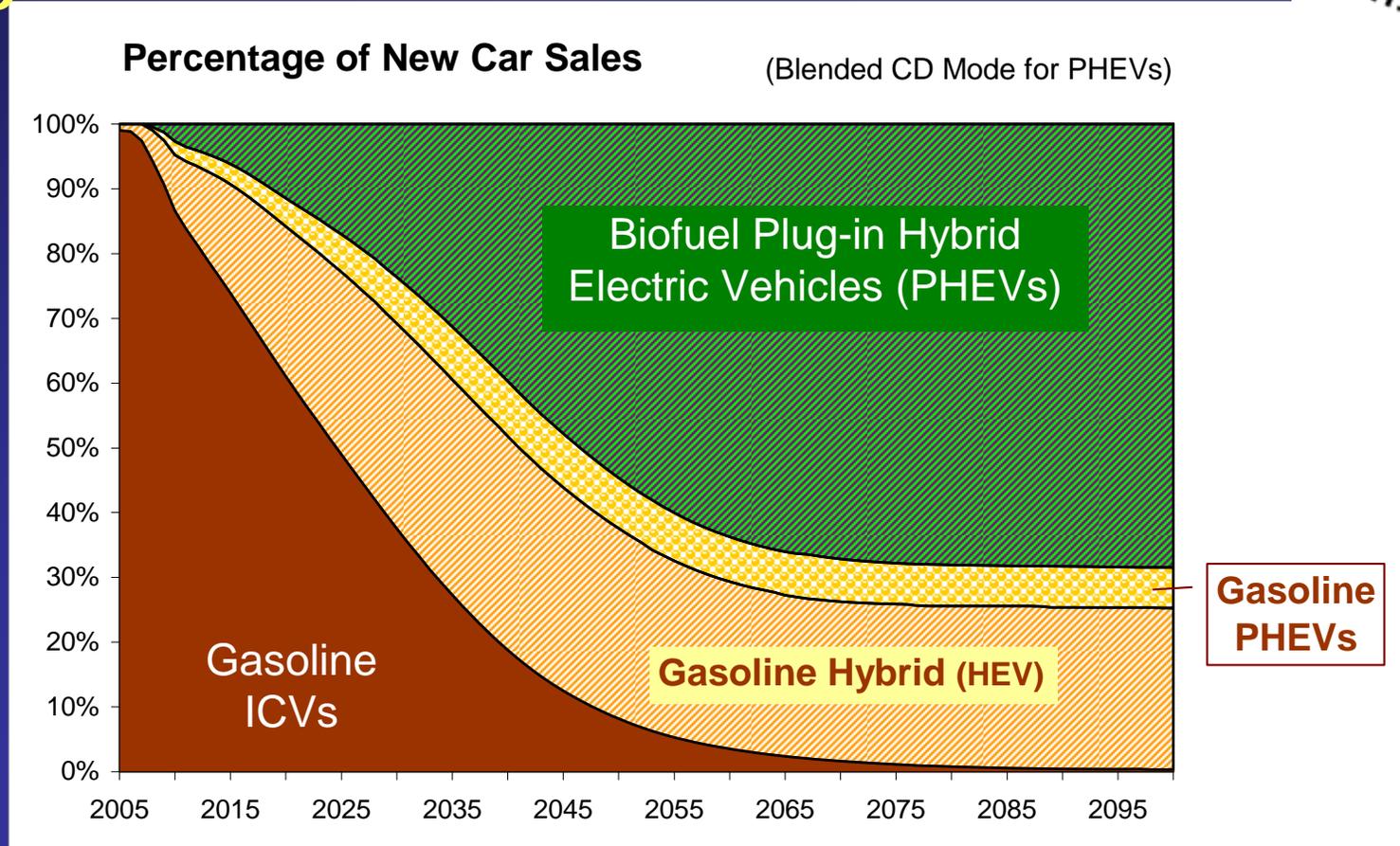


Percentage of New Car Sales



(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)

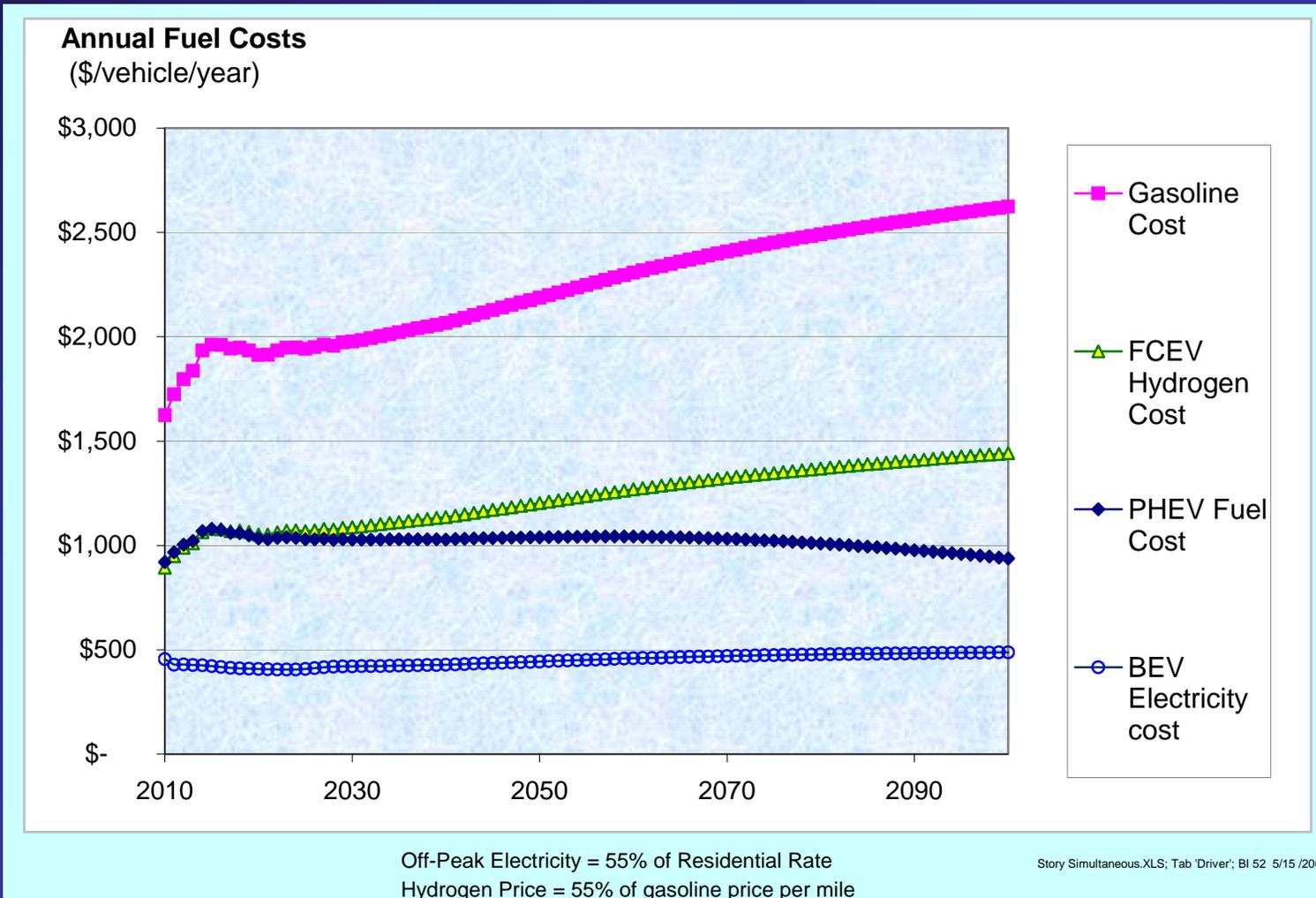
Biofuel (eg. Ethanol) Plug-In Hybrid Scenario Market Shares



(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)

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

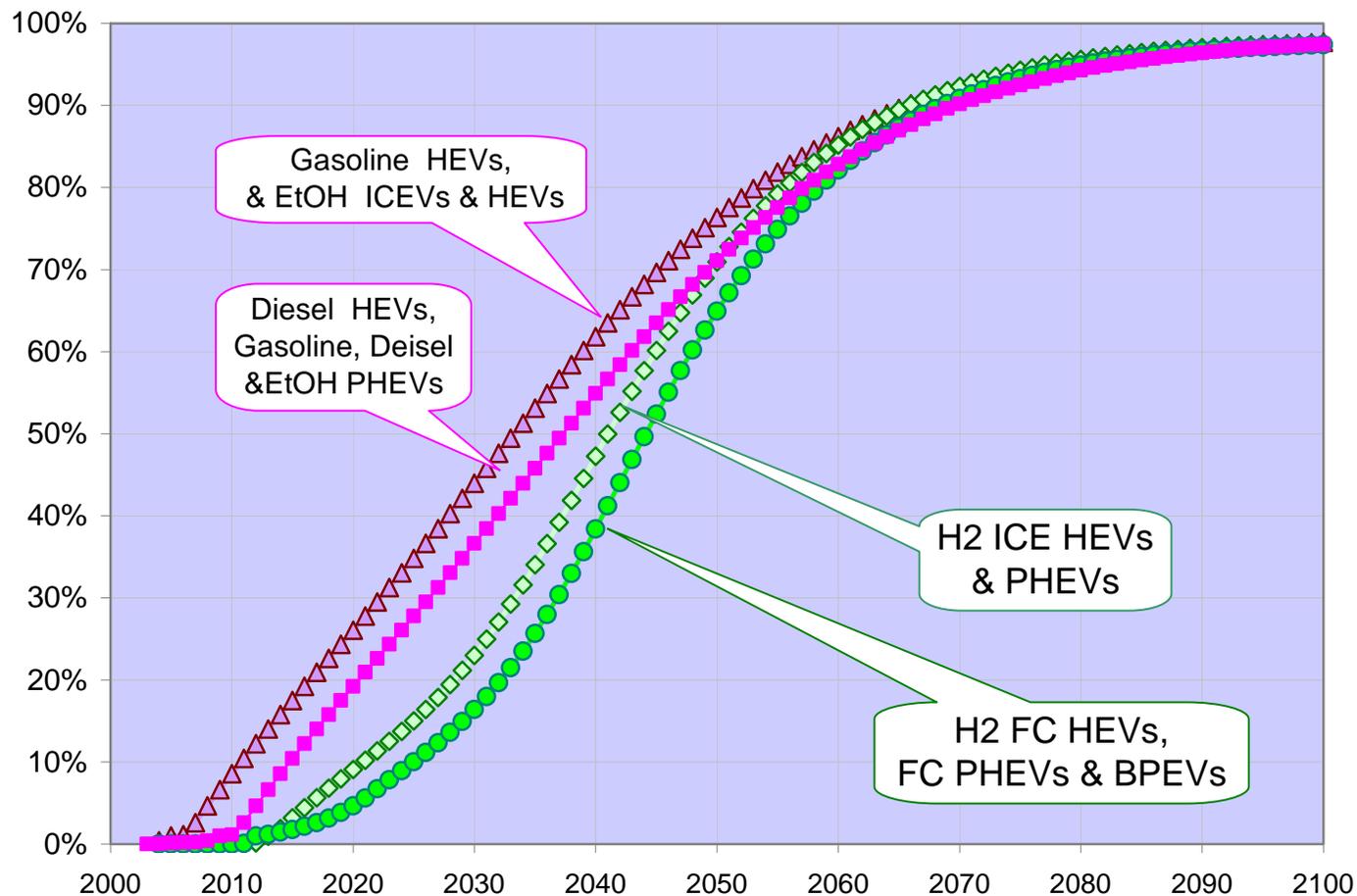
Annual Fuel Costs (\$/car/year)



[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

Market Share of New Car Sales



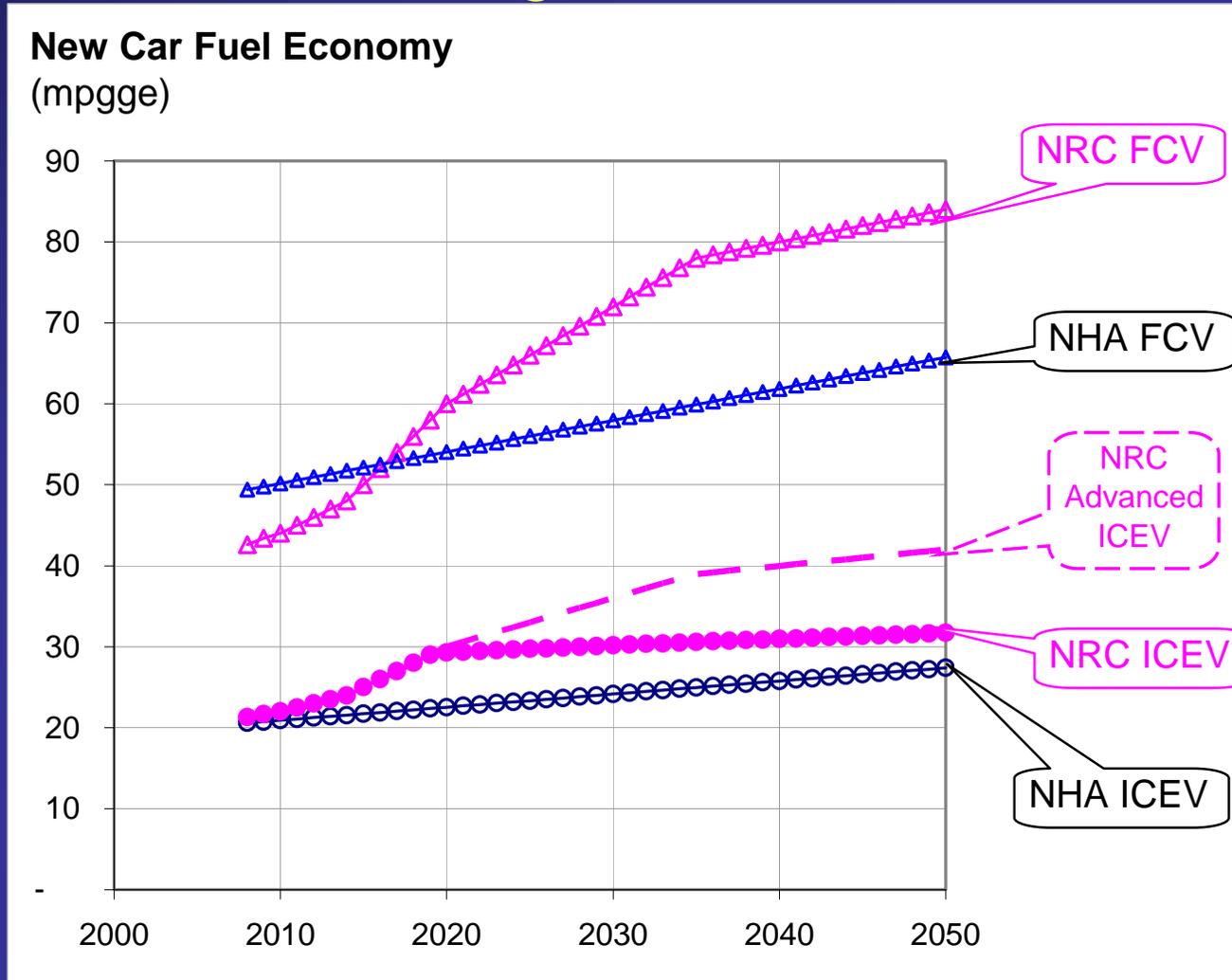
Sensitivity Studies

- NRC comparisons

2008 National Research Council Report vs. NHA Report

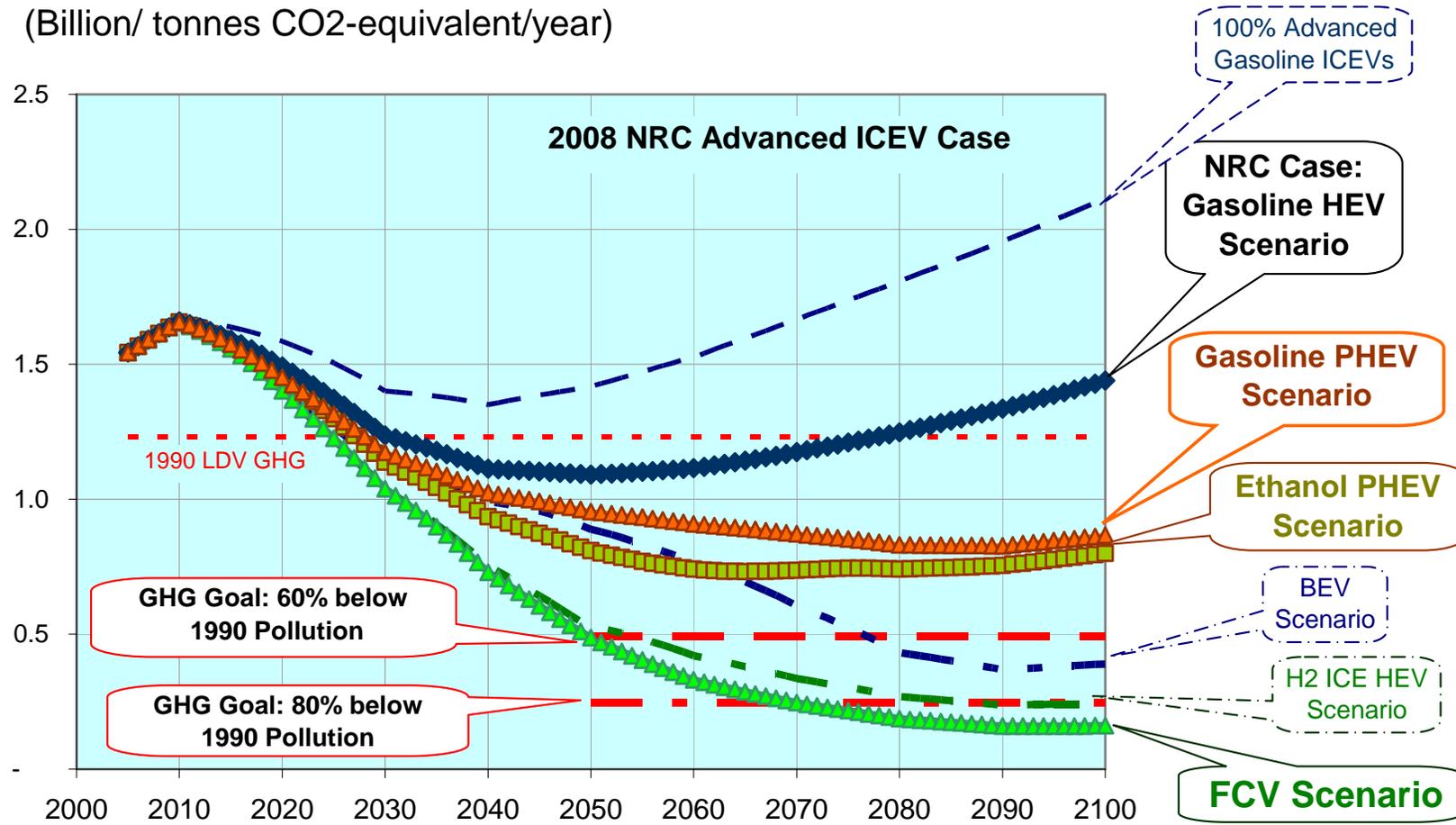
	NRC Assessment	NHA Assessment
Alternative Vehicles Compared:		
Gasoline ICEVs	Yes	Yes
Advanced ICEVs	Yes	Not separately
Gasoline HEVs	Yes	Yes
Gasoline PHEVs	NO	Yes
Ethanol HEVs	Yes ?	Yes
Ethanol PHEVs	NO	Yes
Diesel HEVs	NO	Yes
Diesel PHEVs	NO	Yes
NGVs	NO	Yes
NG HEVs	NO	Yes
NG PHEVs	NO	Yes
H2 ICE HEVs	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)

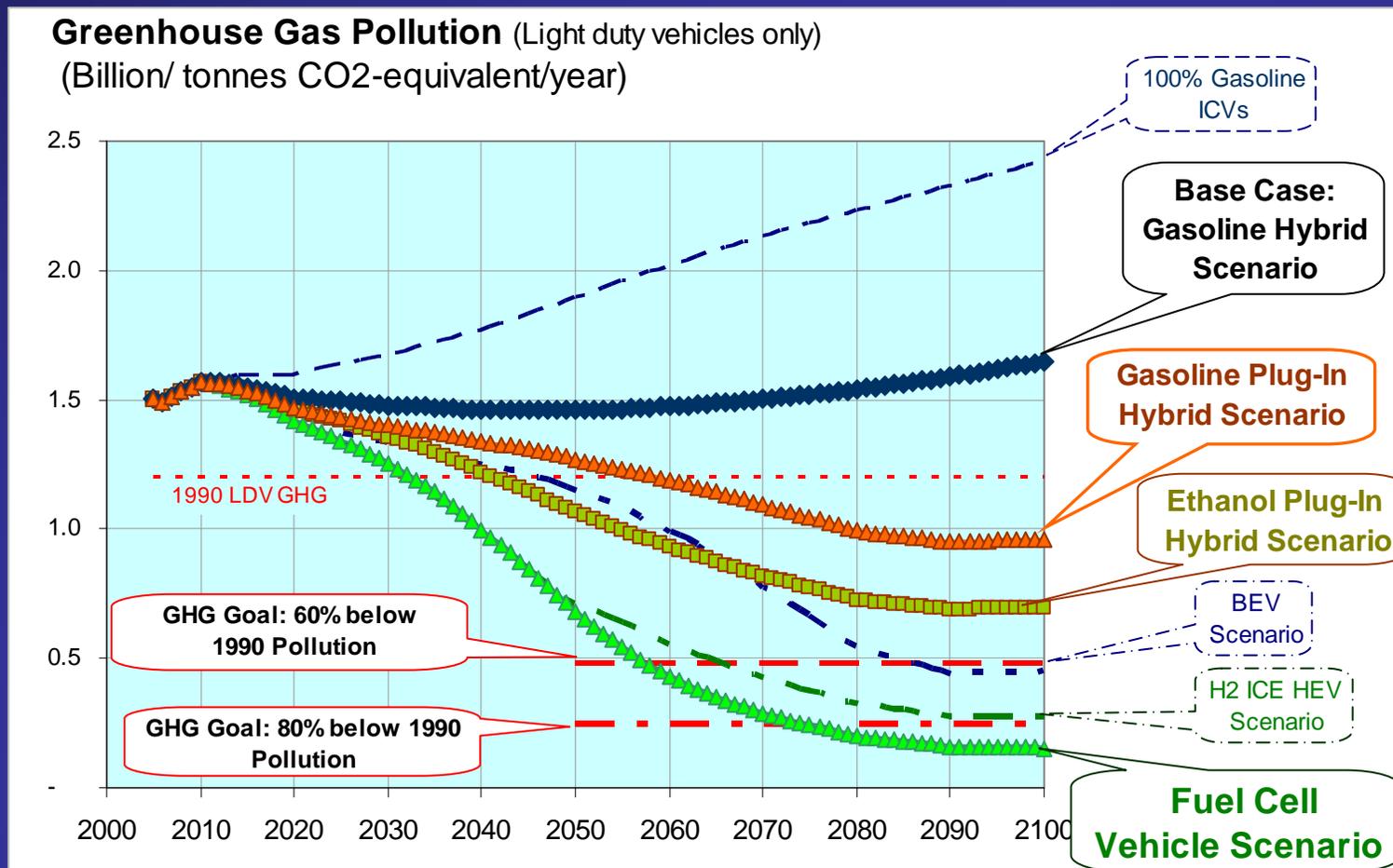


GHG: NHA Model with NRC Input Data

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

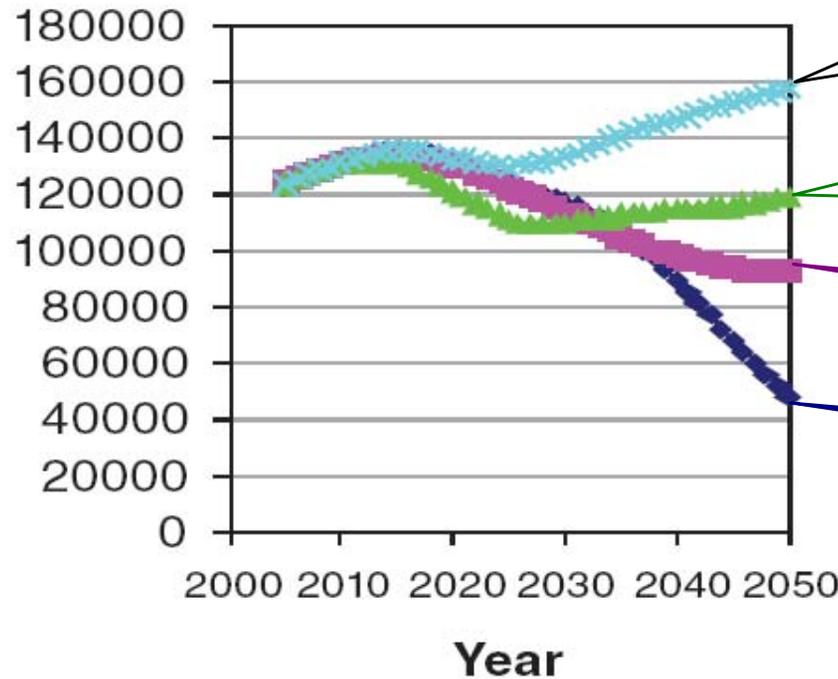


GHG: NHA Model with NHA Input Data



NRC 2008 GHG Results

Gasoline Consumption
(million gallon
gasoline/yr)



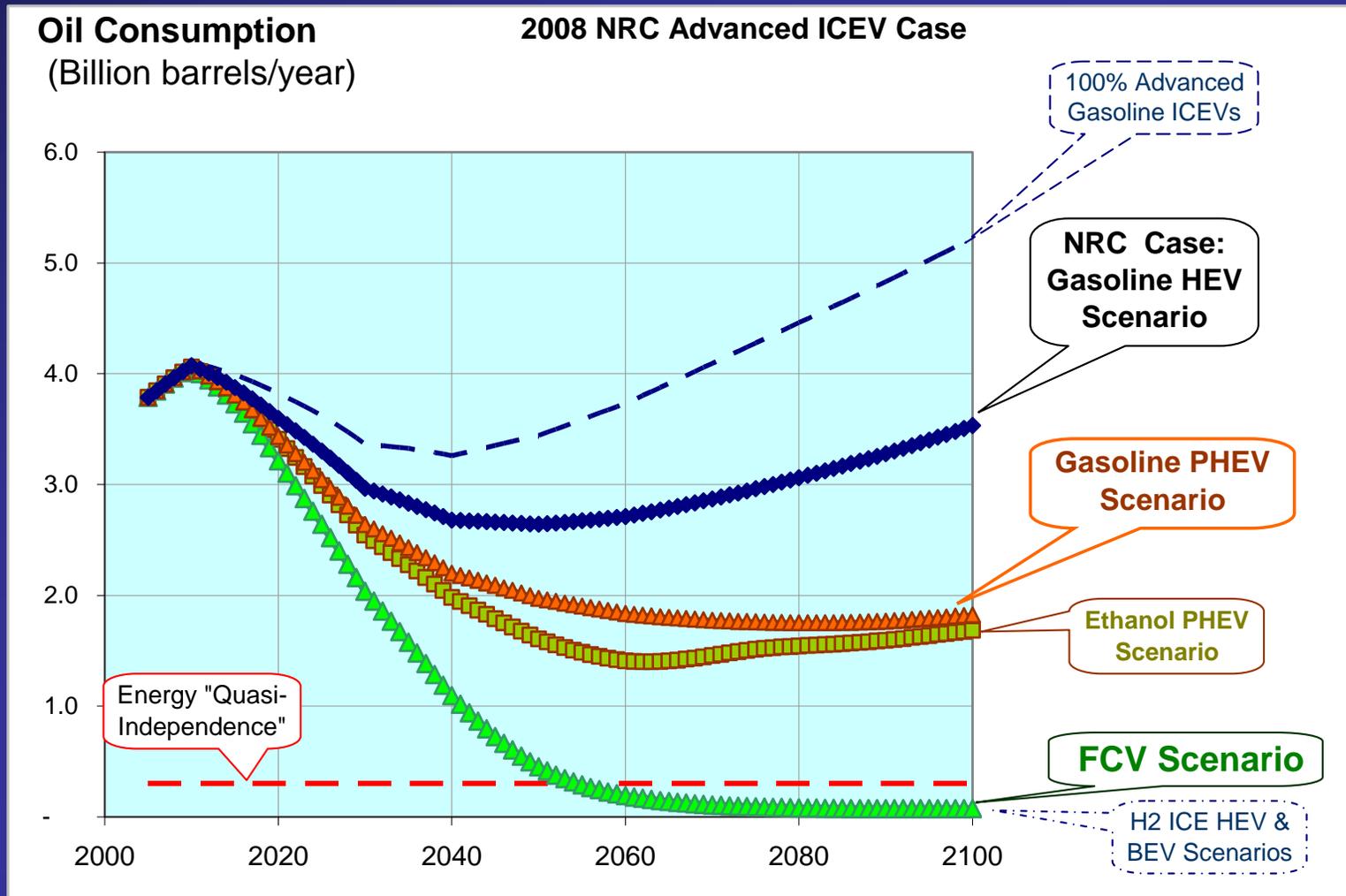
Reference Case

Case 3 (biofuels)

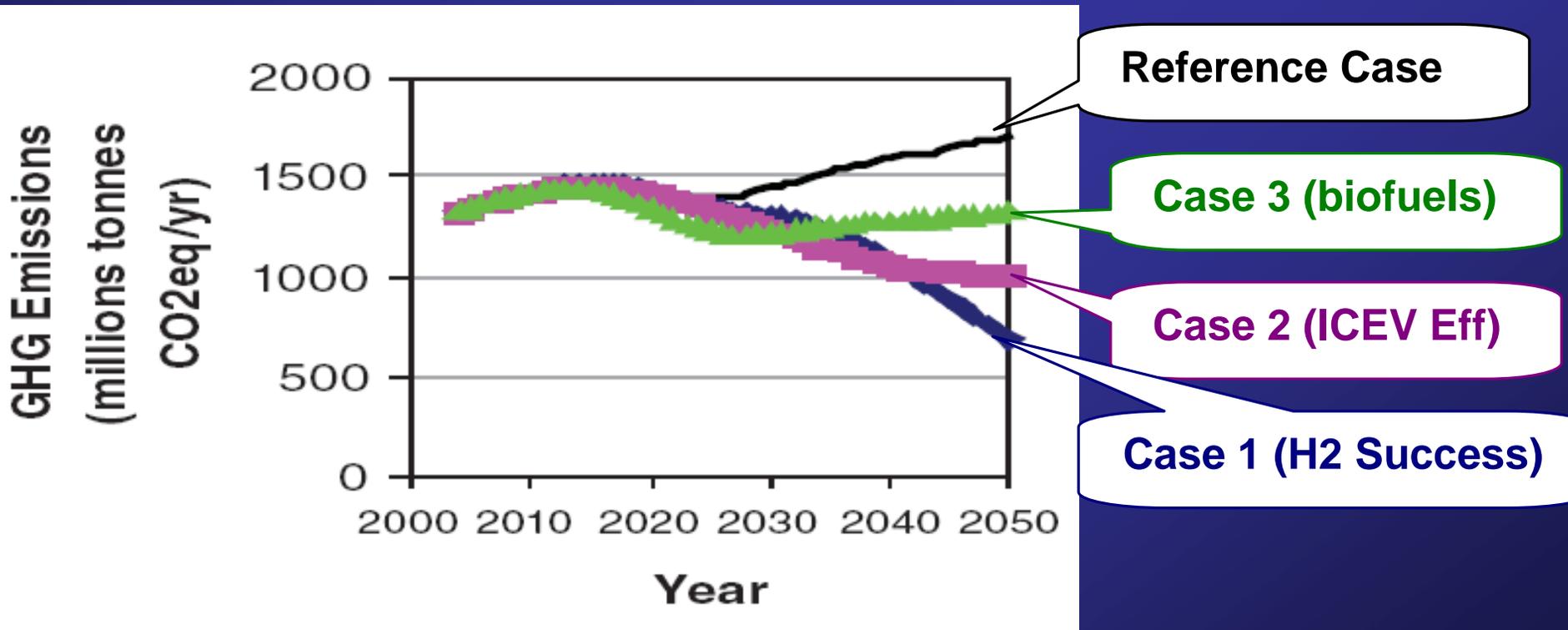
Case 2 (ICEV Eff)

Case 1 (H2 Success)

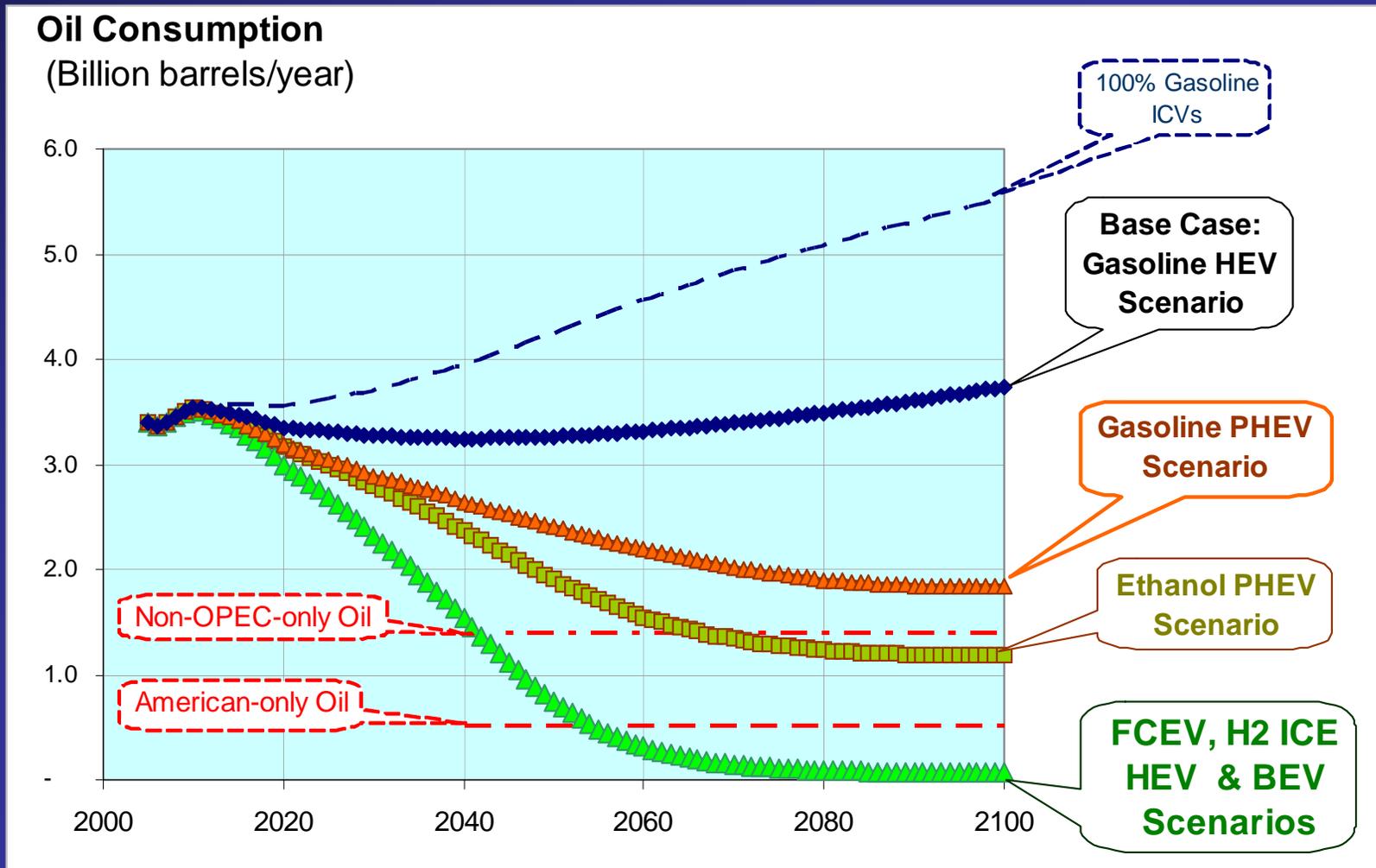
Oil Consumption: NHA Model with NRC Input Data



NRC Oil Consumption



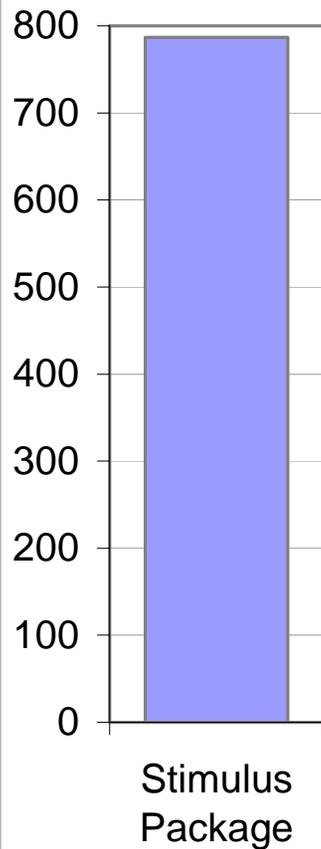
Oil Consumption: NHA Model **H₂Gen** with NHA Input Data



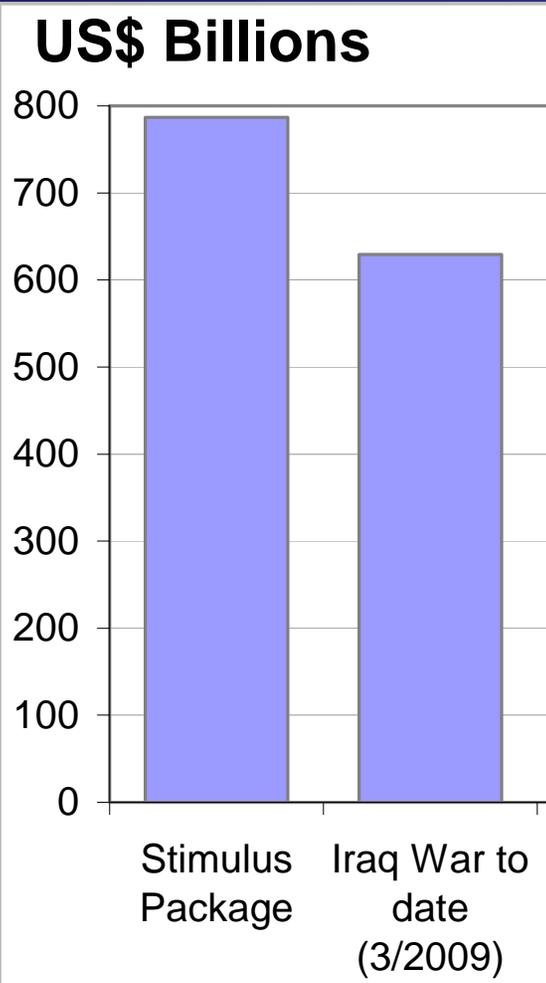
Hydrogen Infrastructure Costs Compared to Other Projects



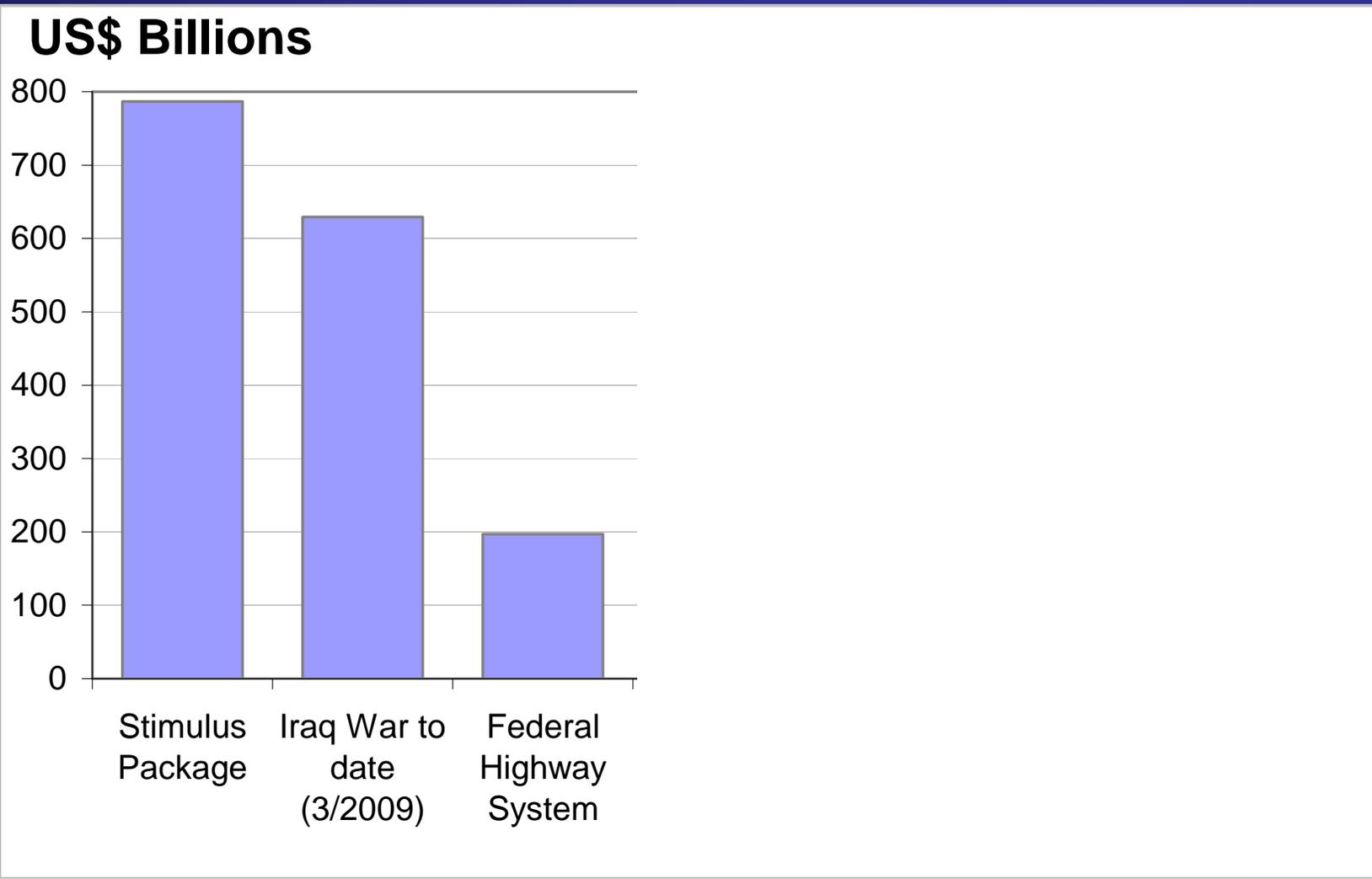
US\$ Billions



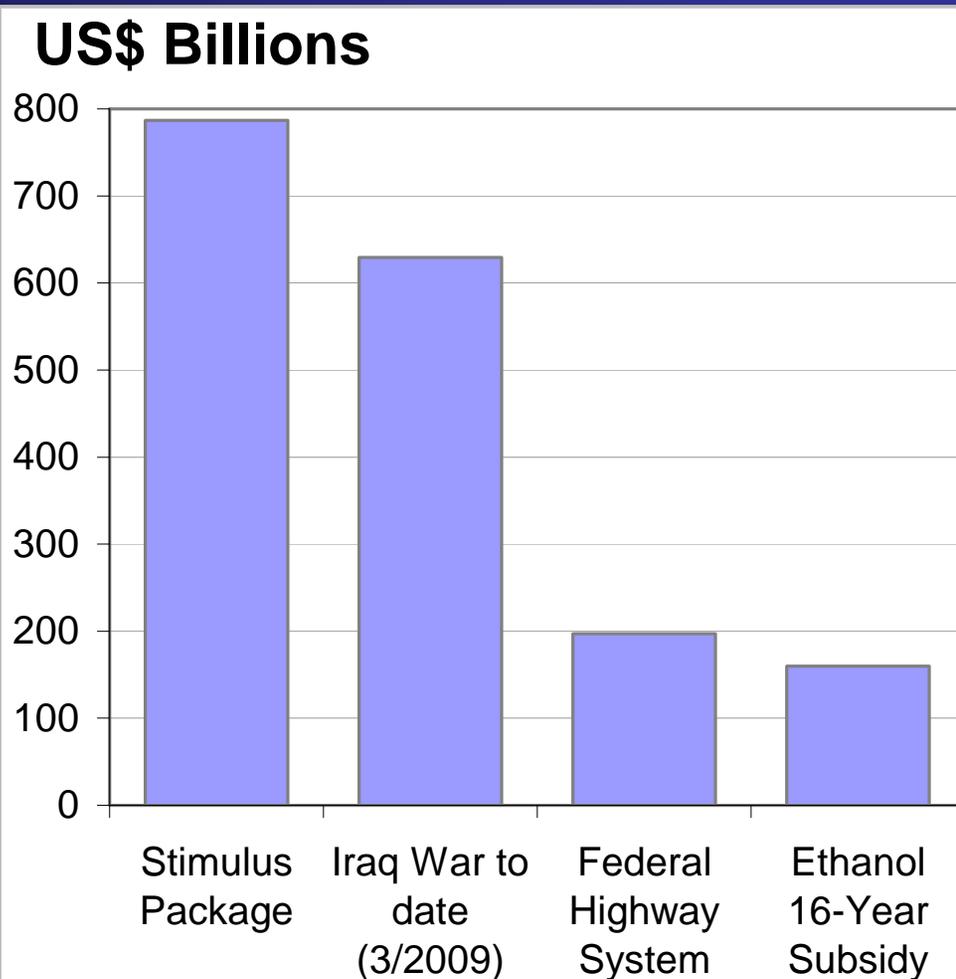
Hydrogen Infrastructure Costs Compared to Other Projects



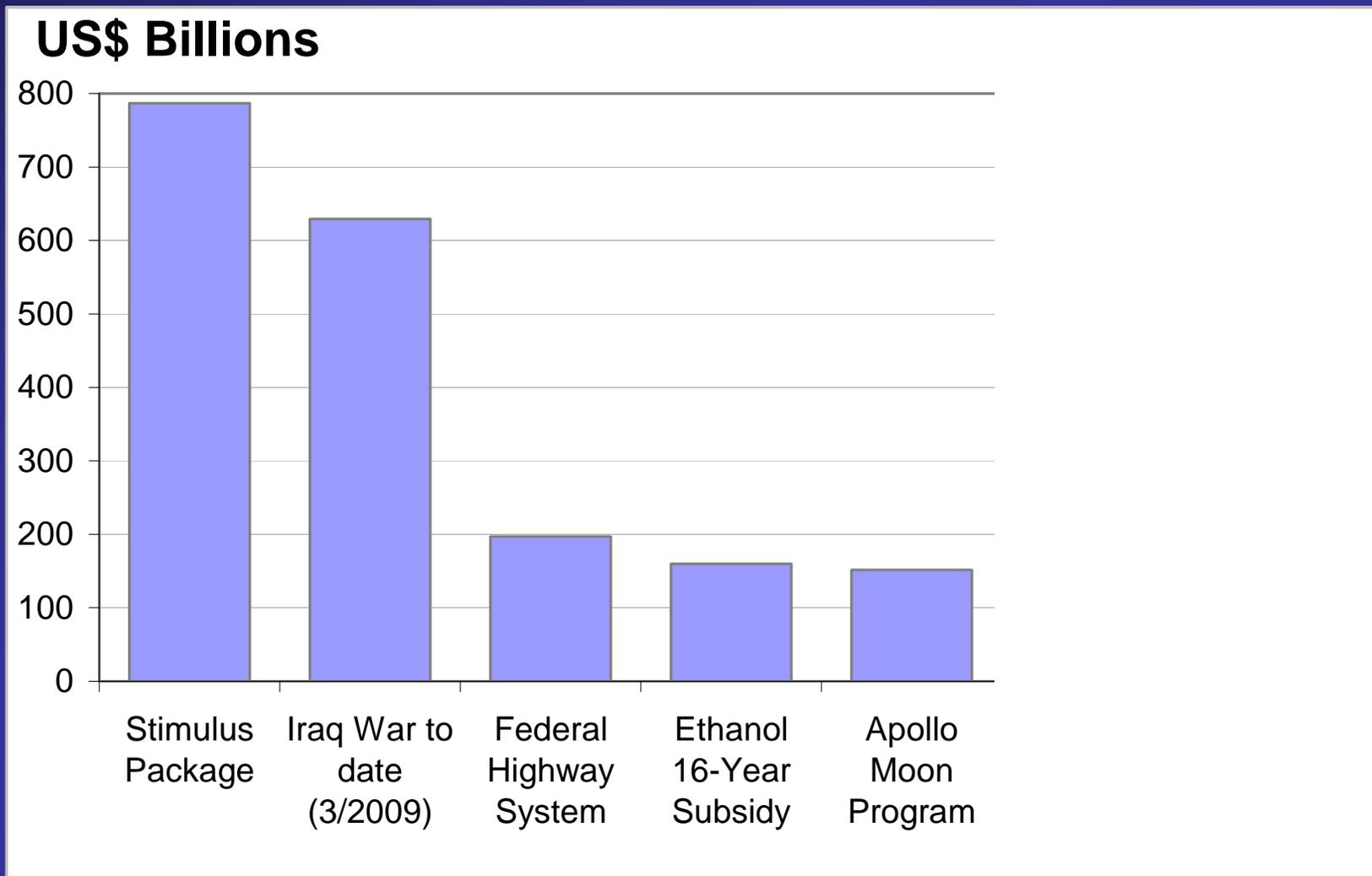
Hydrogen Infrastructure Costs Compared to Other Projects



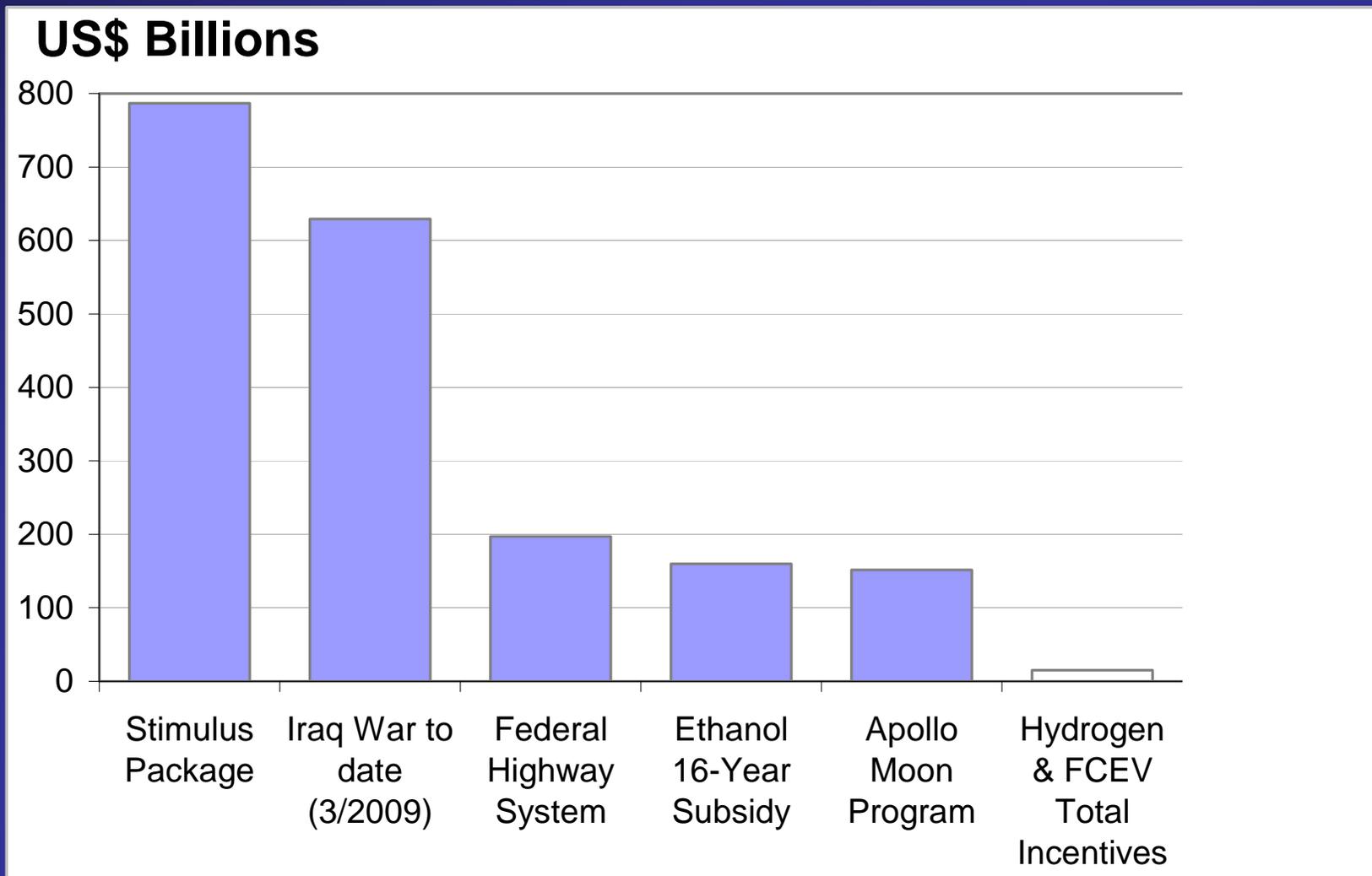
Hydrogen Infrastructure Costs Compared to Other Projects



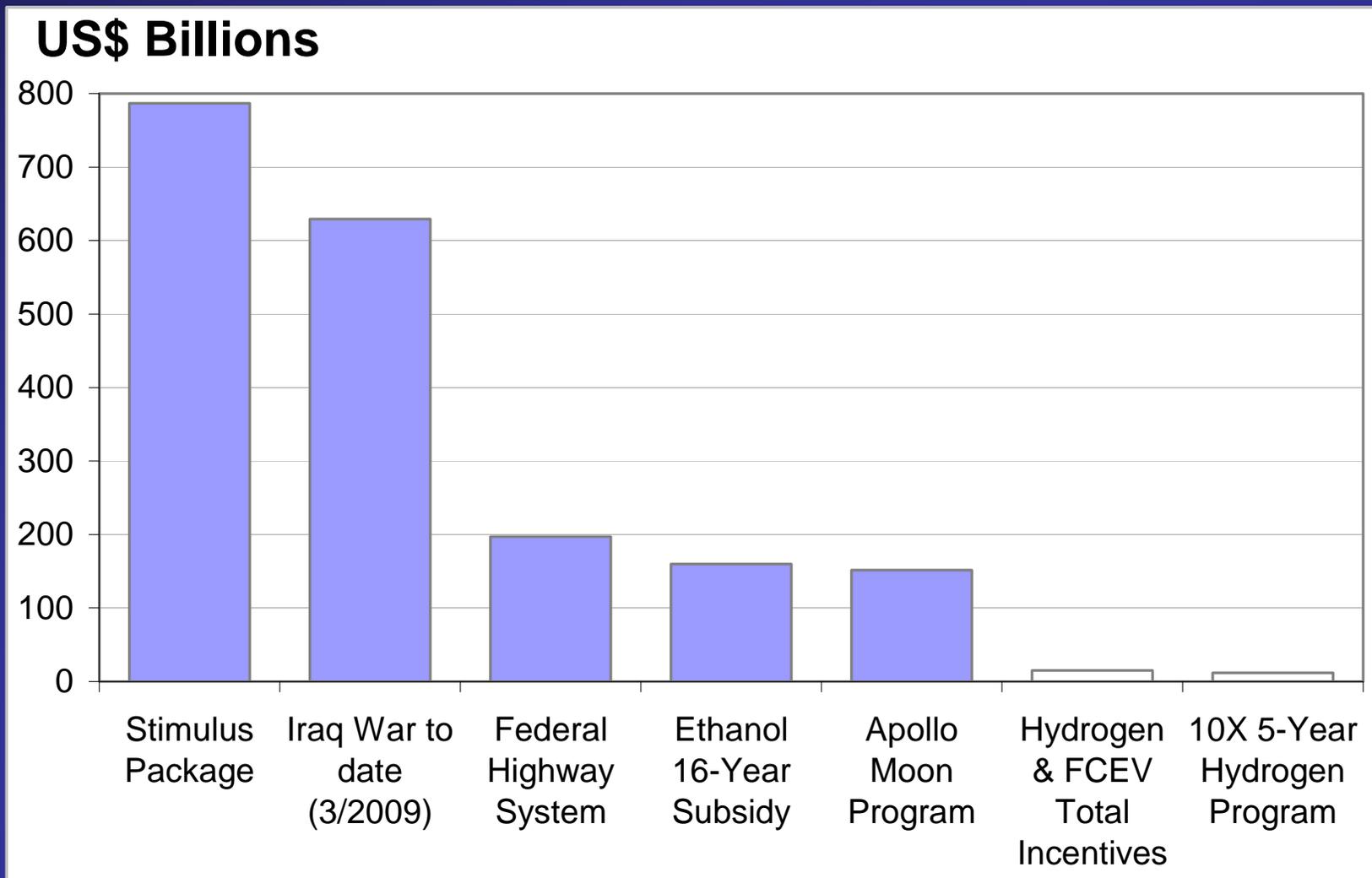
Hydrogen Infrastructure Costs Compared to Other Projects



Hydrogen Infrastructure Costs Compared to Other Projects

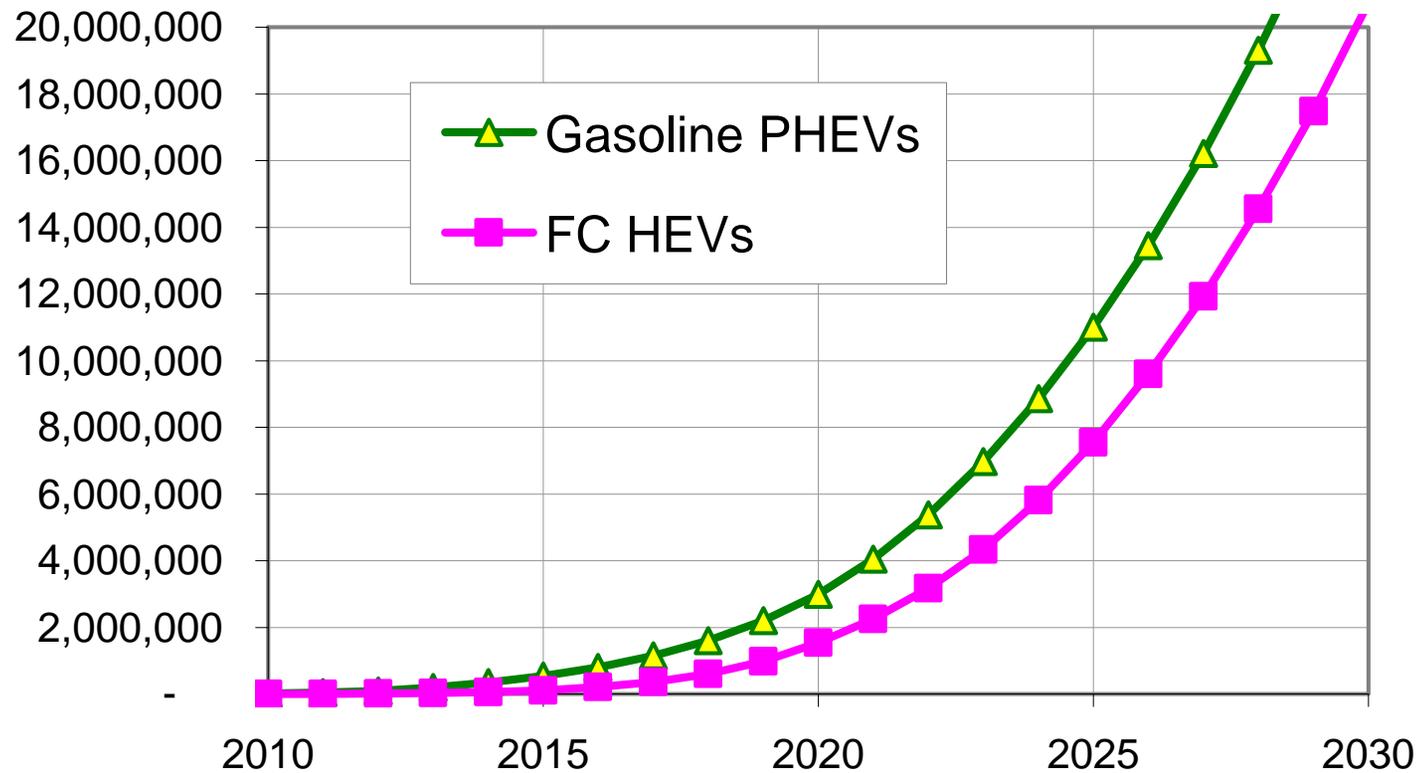


Hydrogen Infrastructure Costs Compared to Other Projects



Number of Vehicles on the road

Number of Vehicles on the road



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

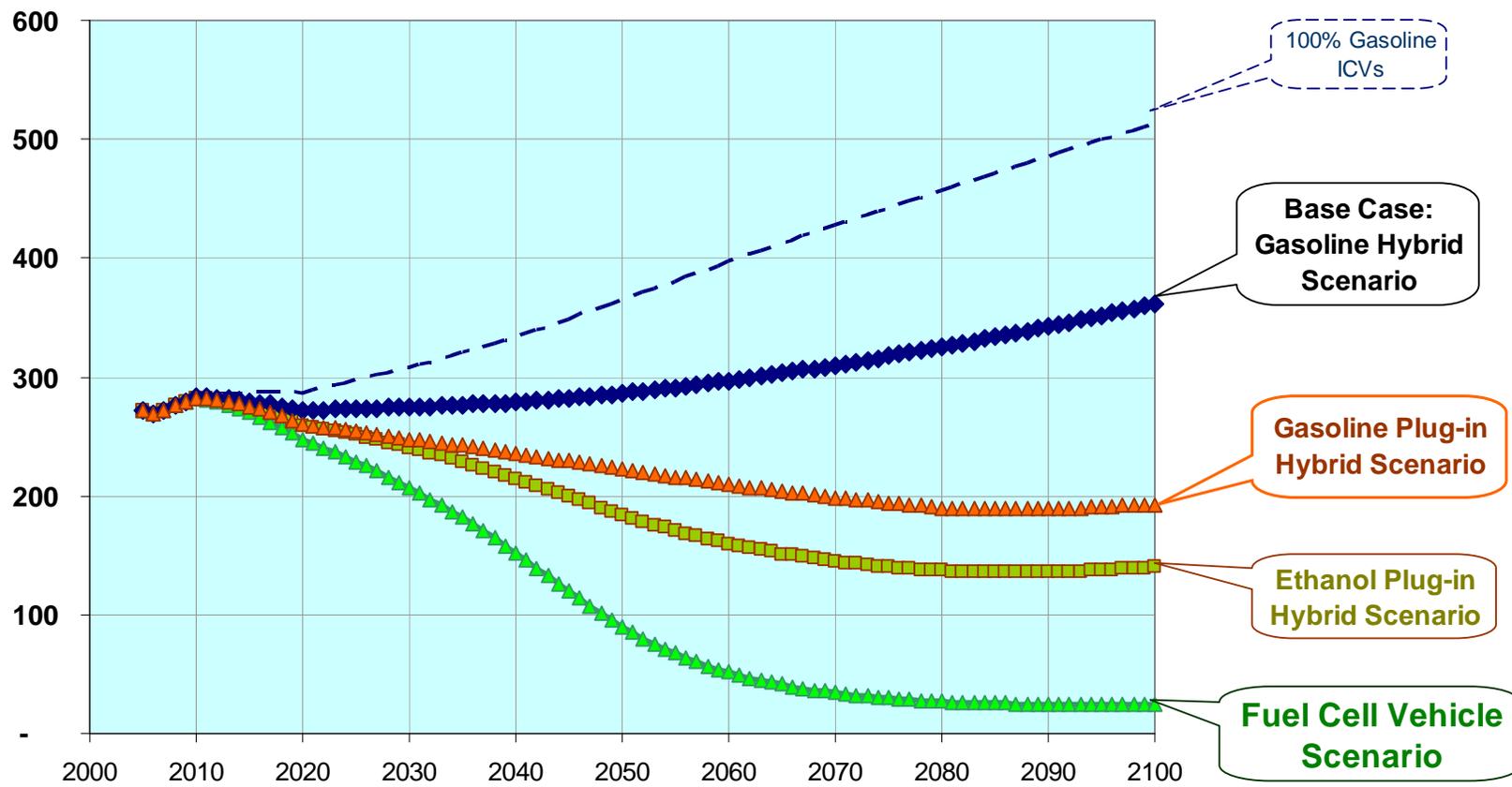
Financial & Performance Data used in Model

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

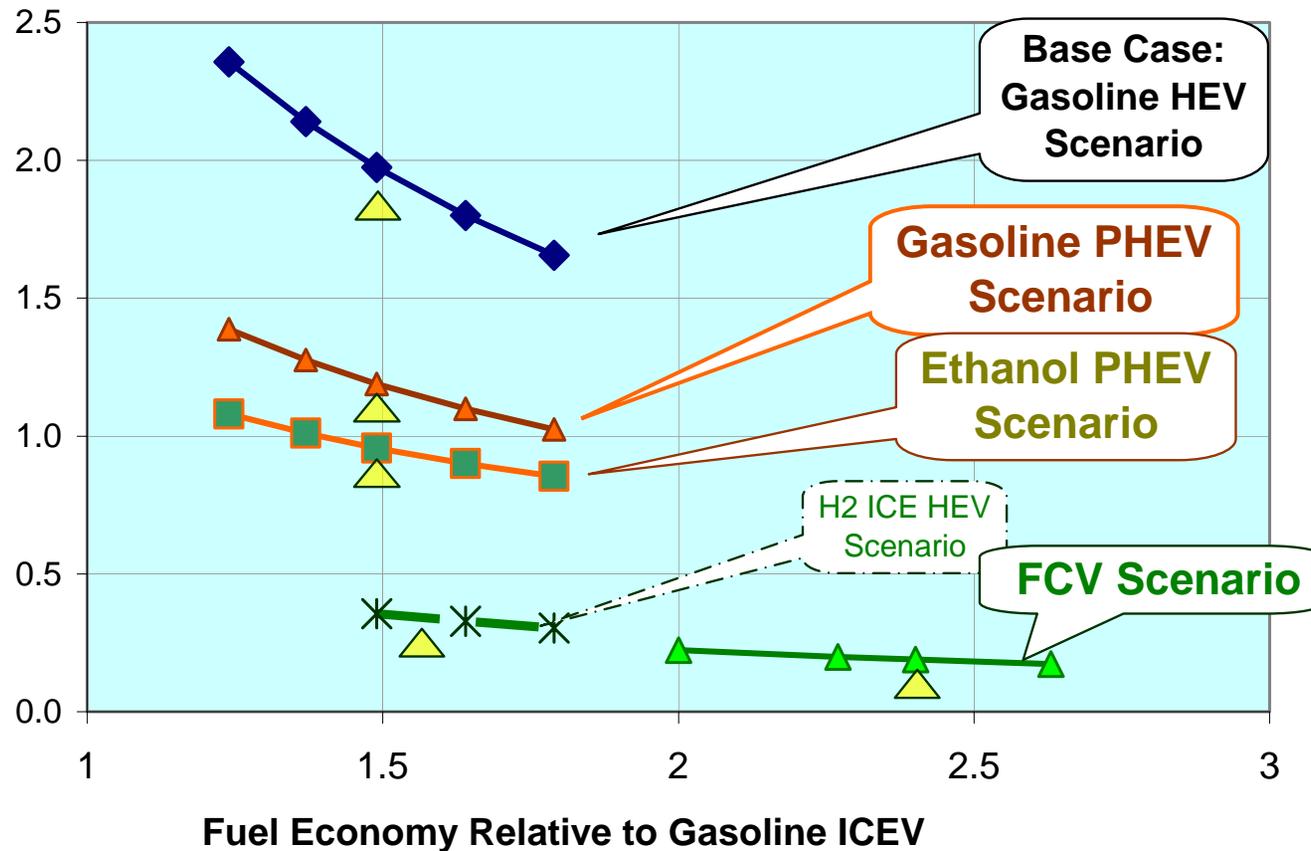
Total Societal Costs
(\$Billion/year)



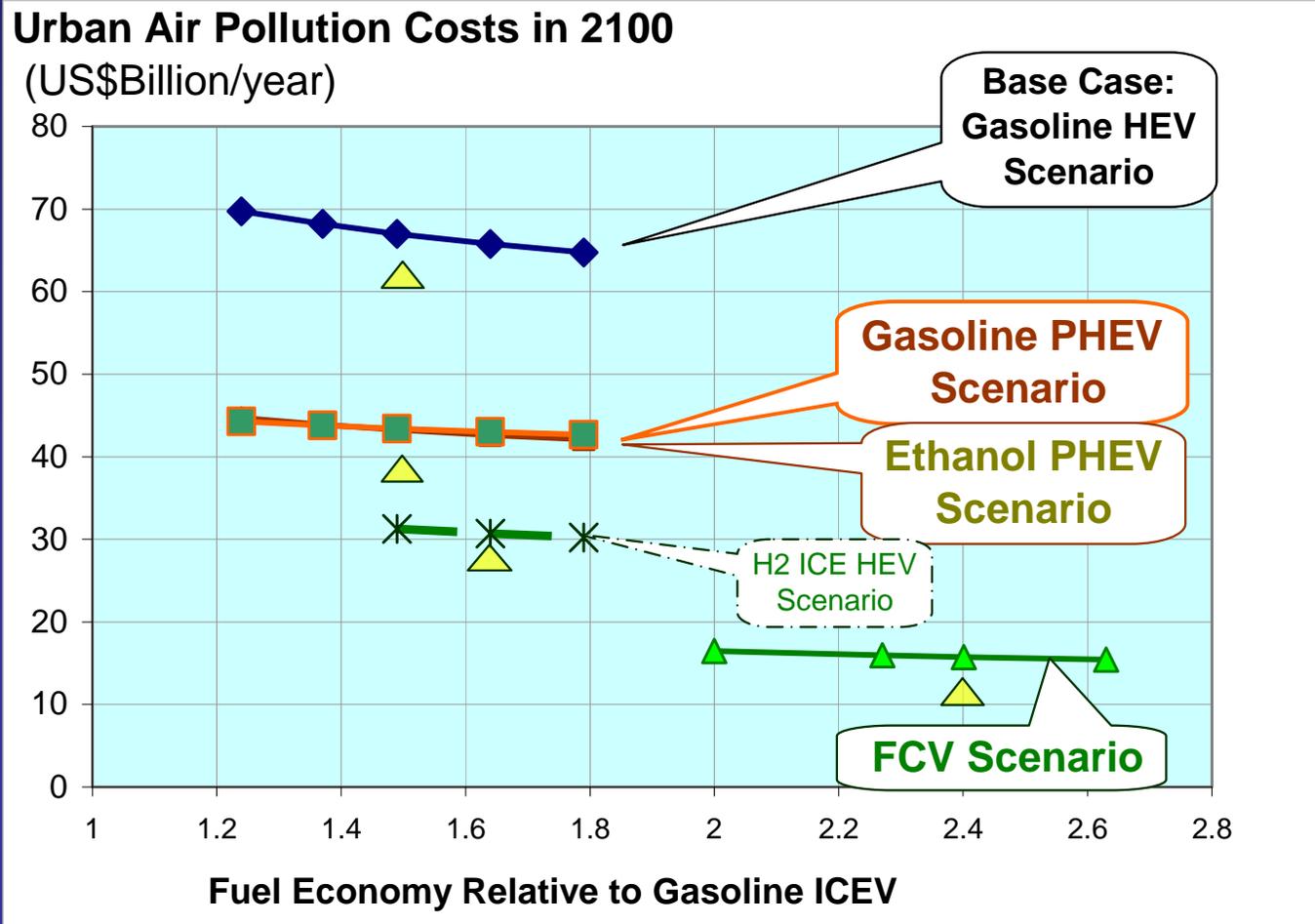
Sensitivity to Fuel Economy

Greenhouse Gas Sensitivity to Vehicle Fuel Economy

Greenhouse Gas Pollution in 2100 (Light duty vehicles only)
 (Billion metric tonnes CO₂-equivalent/year)

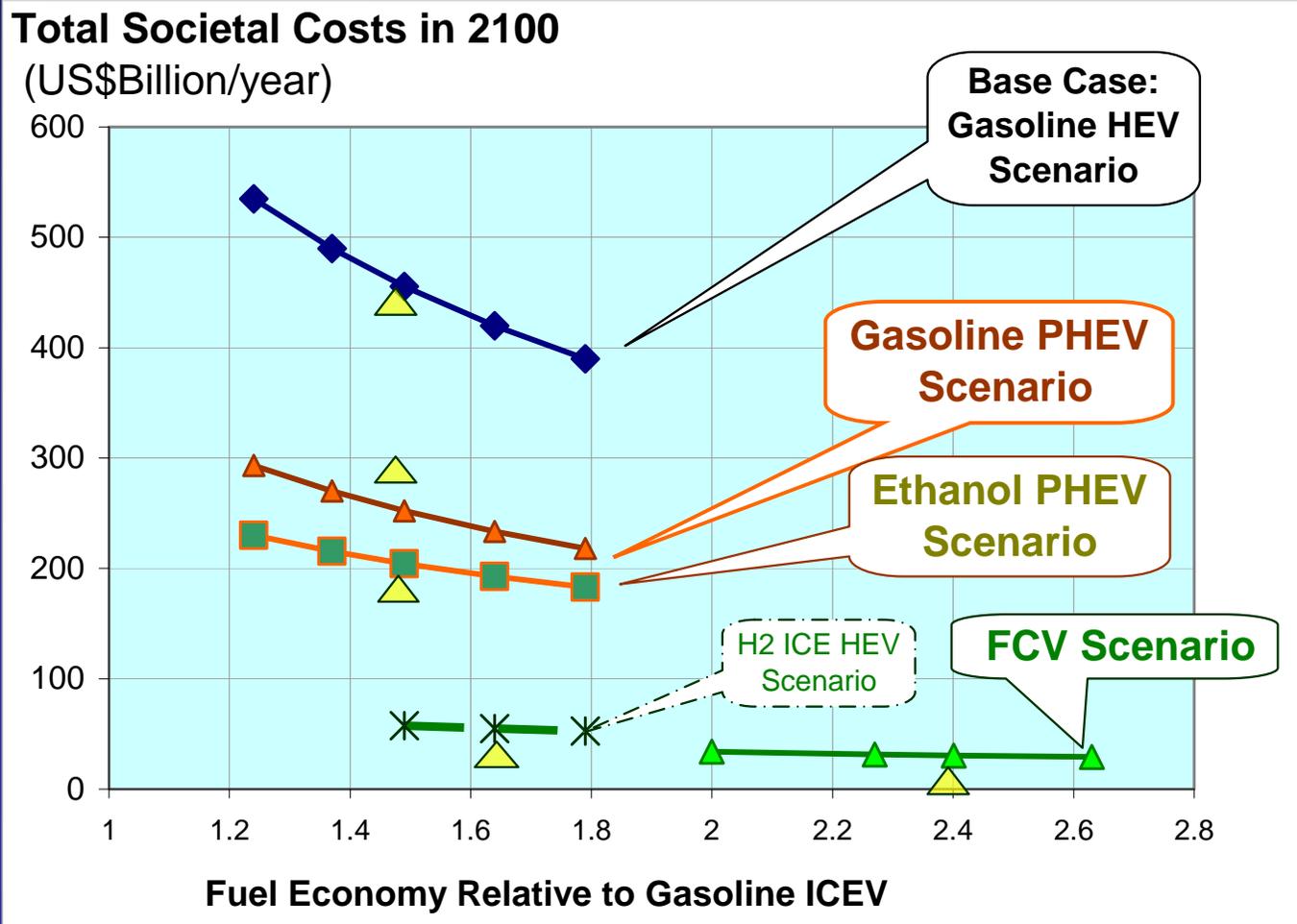


Urban Air Pollution Sensitivity to Vehicle Fuel Economy



Based on old AEO 2008 data

Societal Cost Sensitivity to Vehicle Fuel Economy



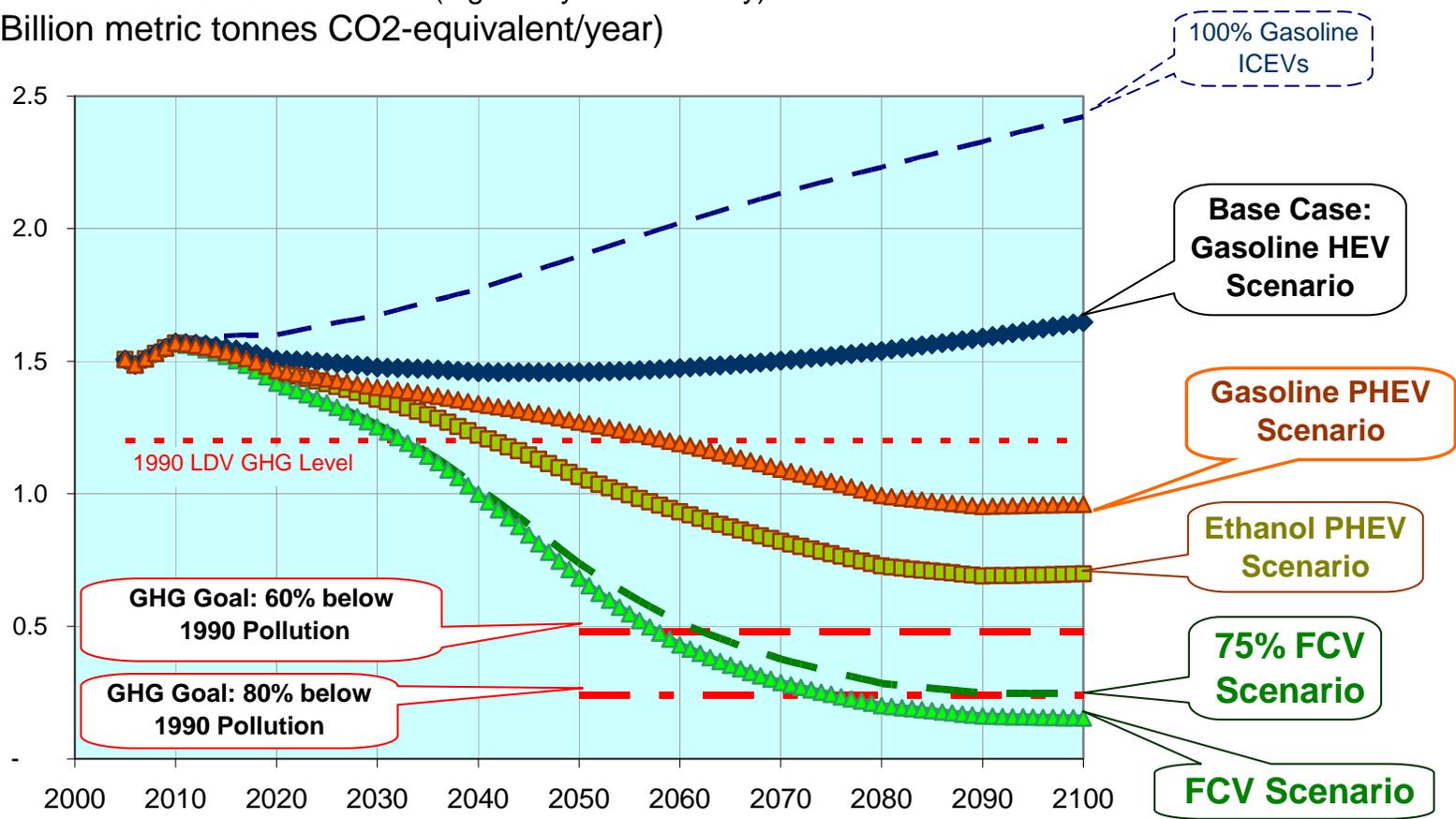
Based on old AEO 2008 data

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

Sensitivity to FCEV Market Share & Carbon Footprints

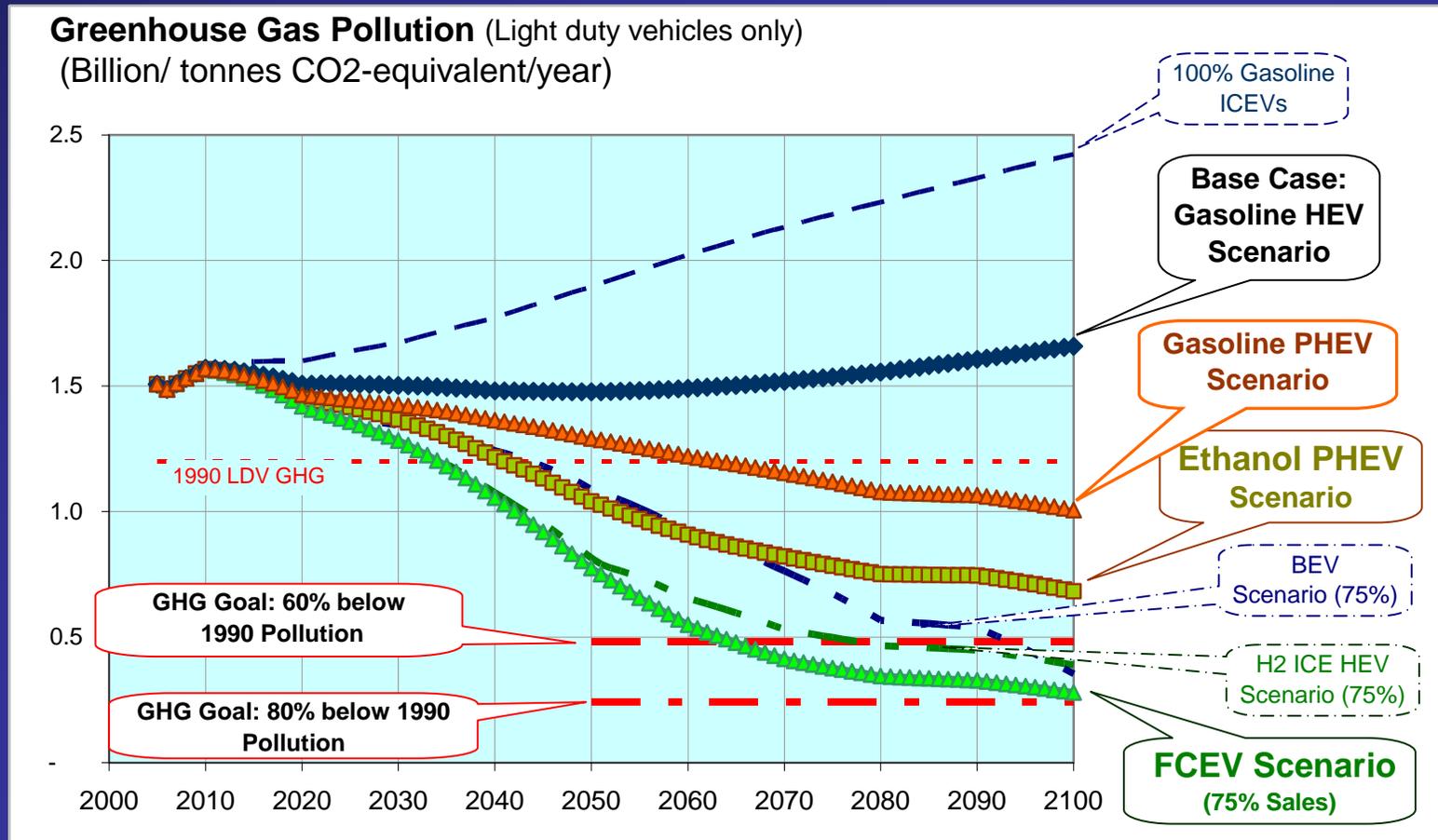
Greenhouse Gases with 75% FCEV Market Limit

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



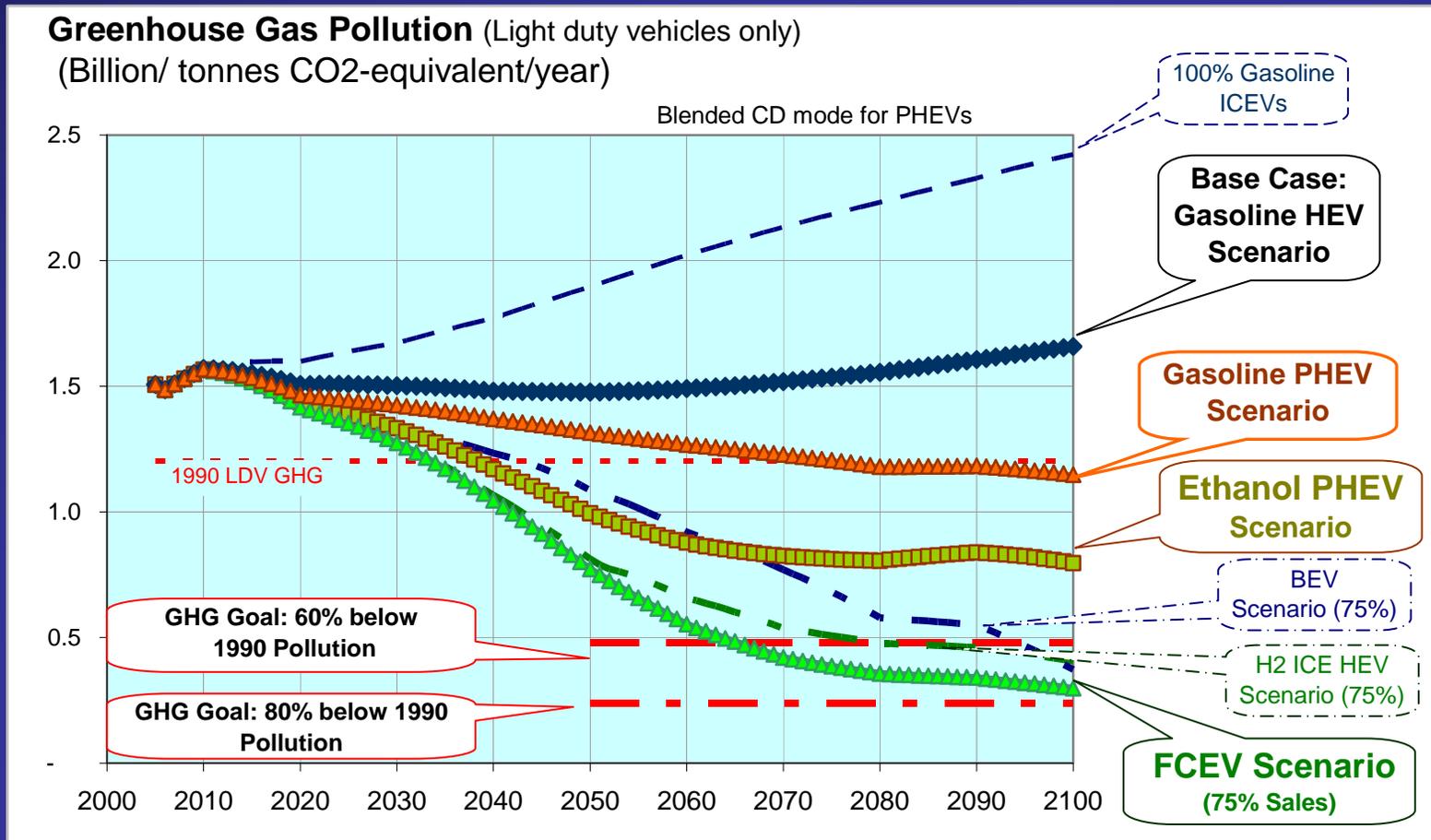
Greenhouse Gases

with 75% FCEV Limit & DOE Carbon parameters
 (Greener grid and less green hydrogen; all-electric CD mode for PHEVs)

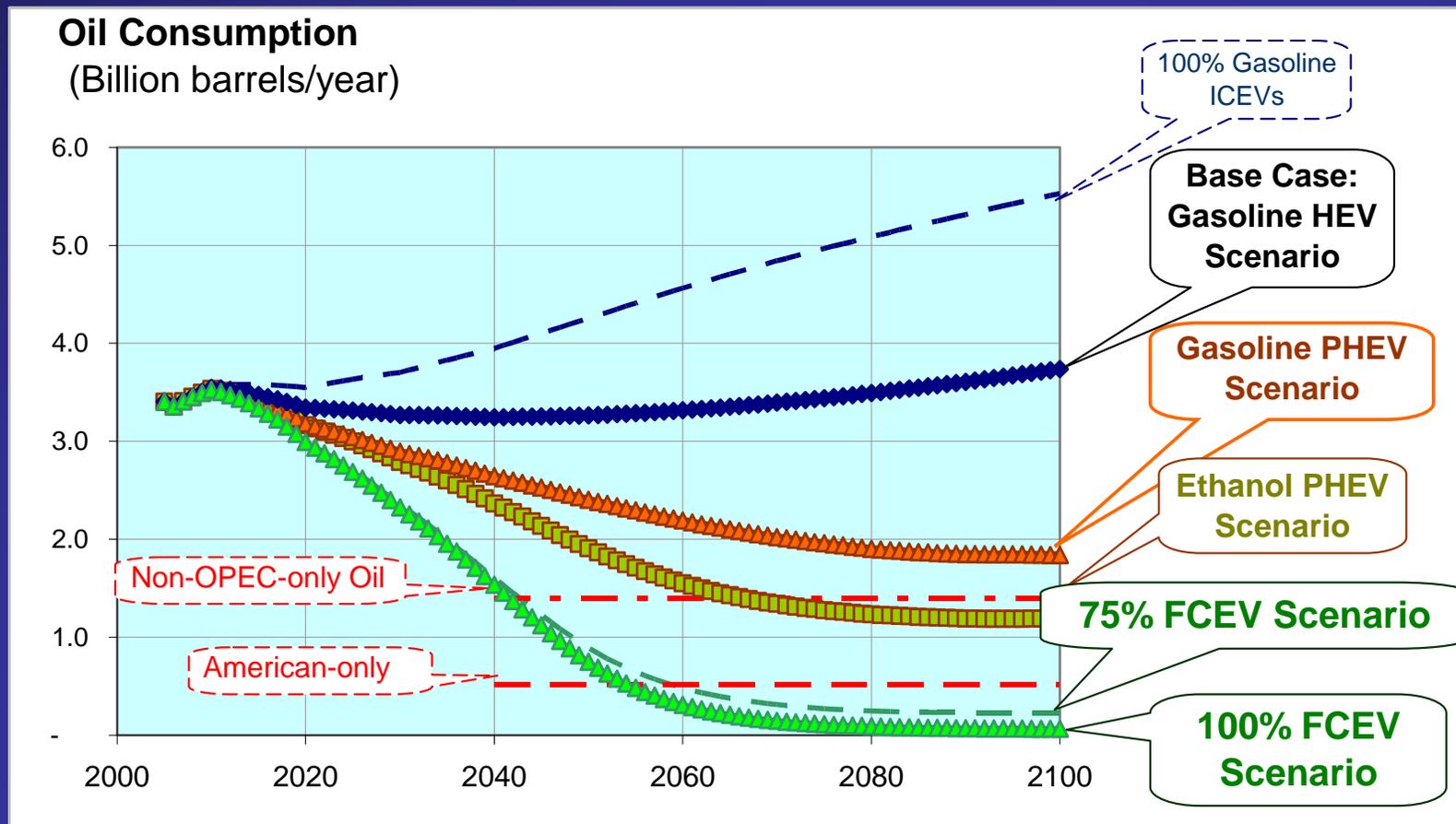


Greenhouse Gases

with 75% FCEV Limit & DOE Carbon parameters
 (Greener grid and less green hydrogen & Blended CD mode for PHEVs)

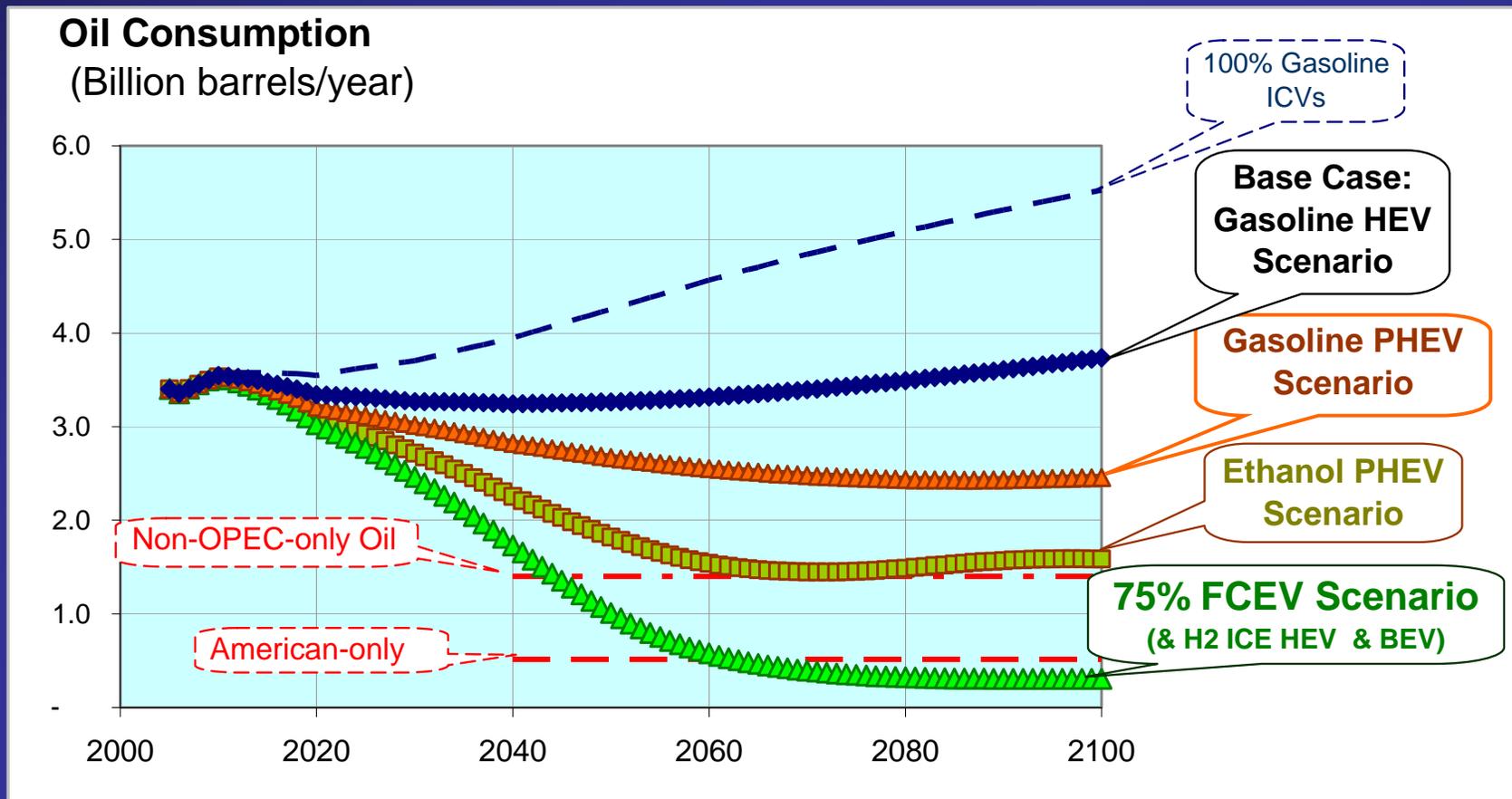


Oil Consumption with 75% FCEV Market Limit

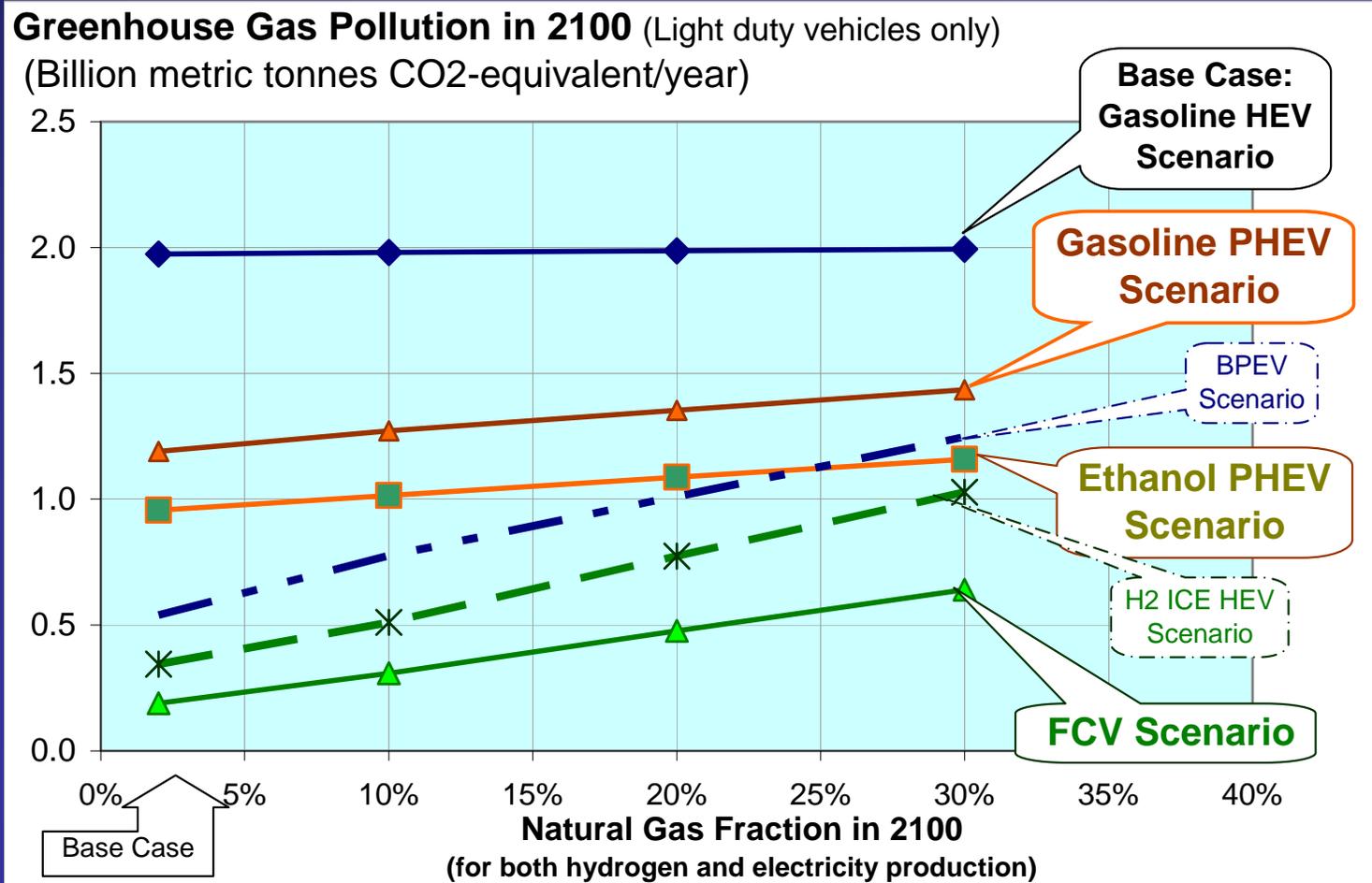


Oil Consumption

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



GHG Sensitivity to NG Fraction (electricity & hydrogen source)

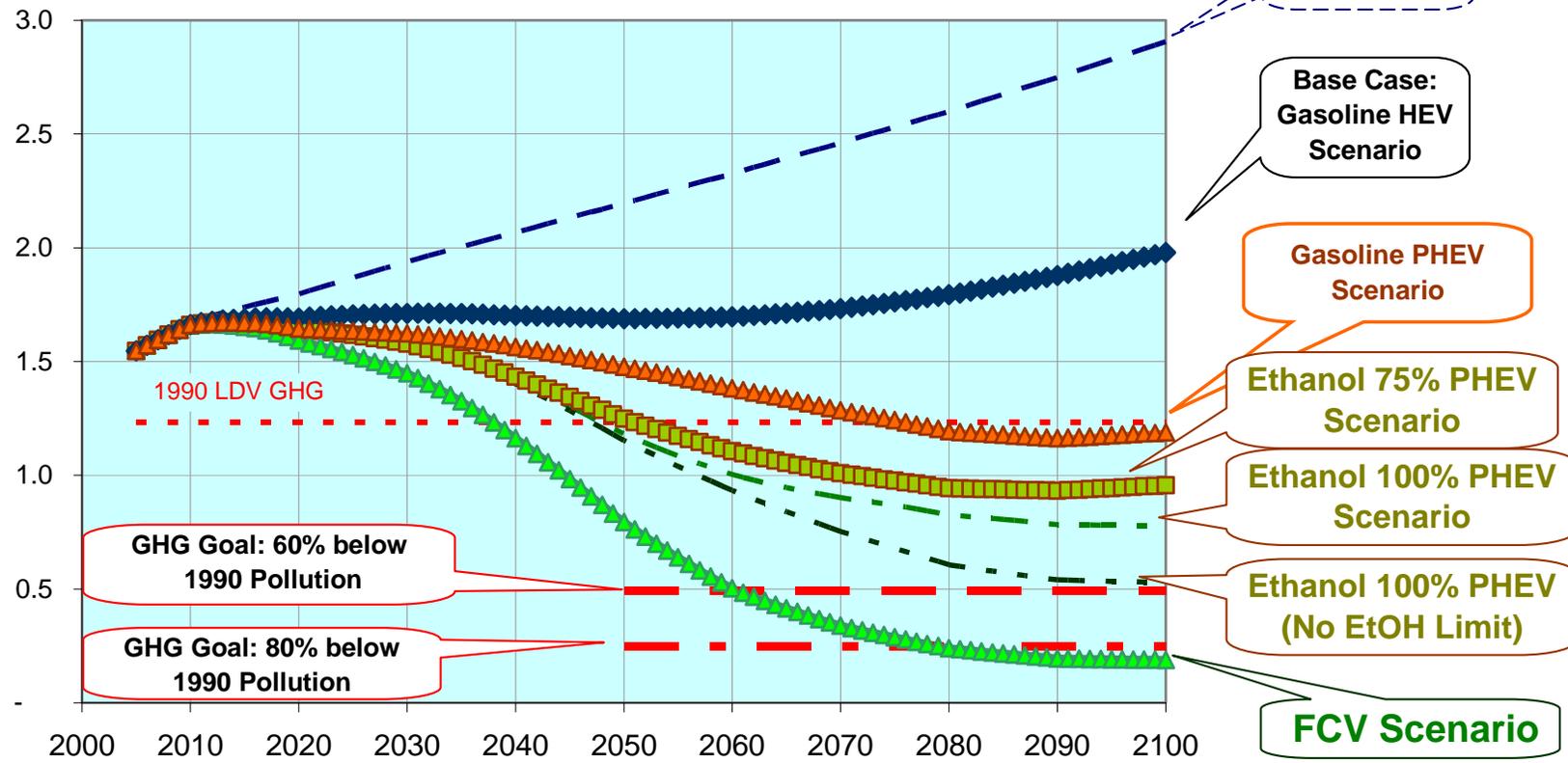


Based on old AEO 2008 data

Sensitivity to Ethanol PHEV Market share

GHG Sensitivity to Ethanol Production Capacity & Plug-in Capacity

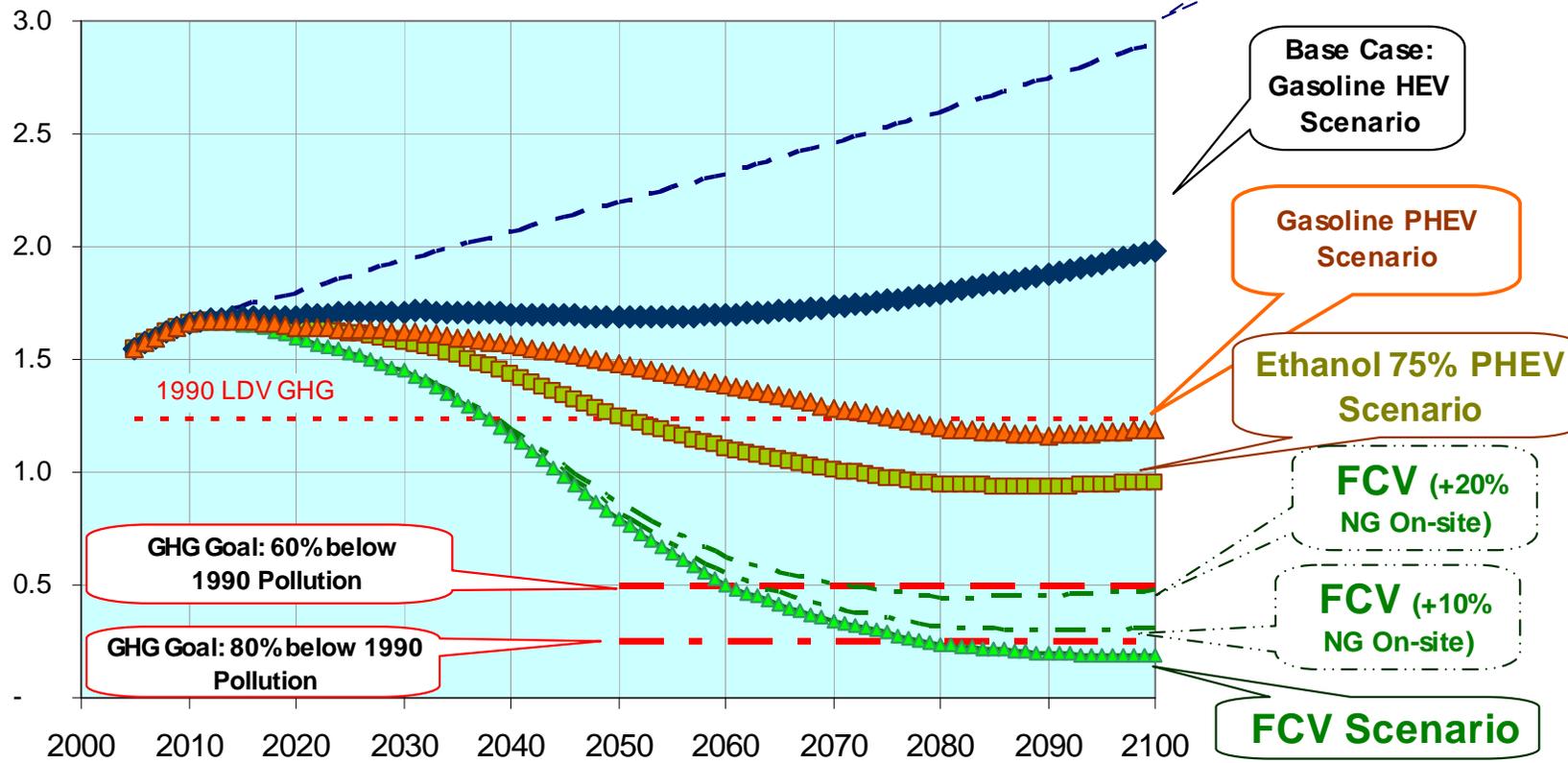
Greenhouse Gas Pollution (Light duty vehicles only)
(Billion/ tonnes CO₂-equivalent/year)



Based on old AEO 2008 data

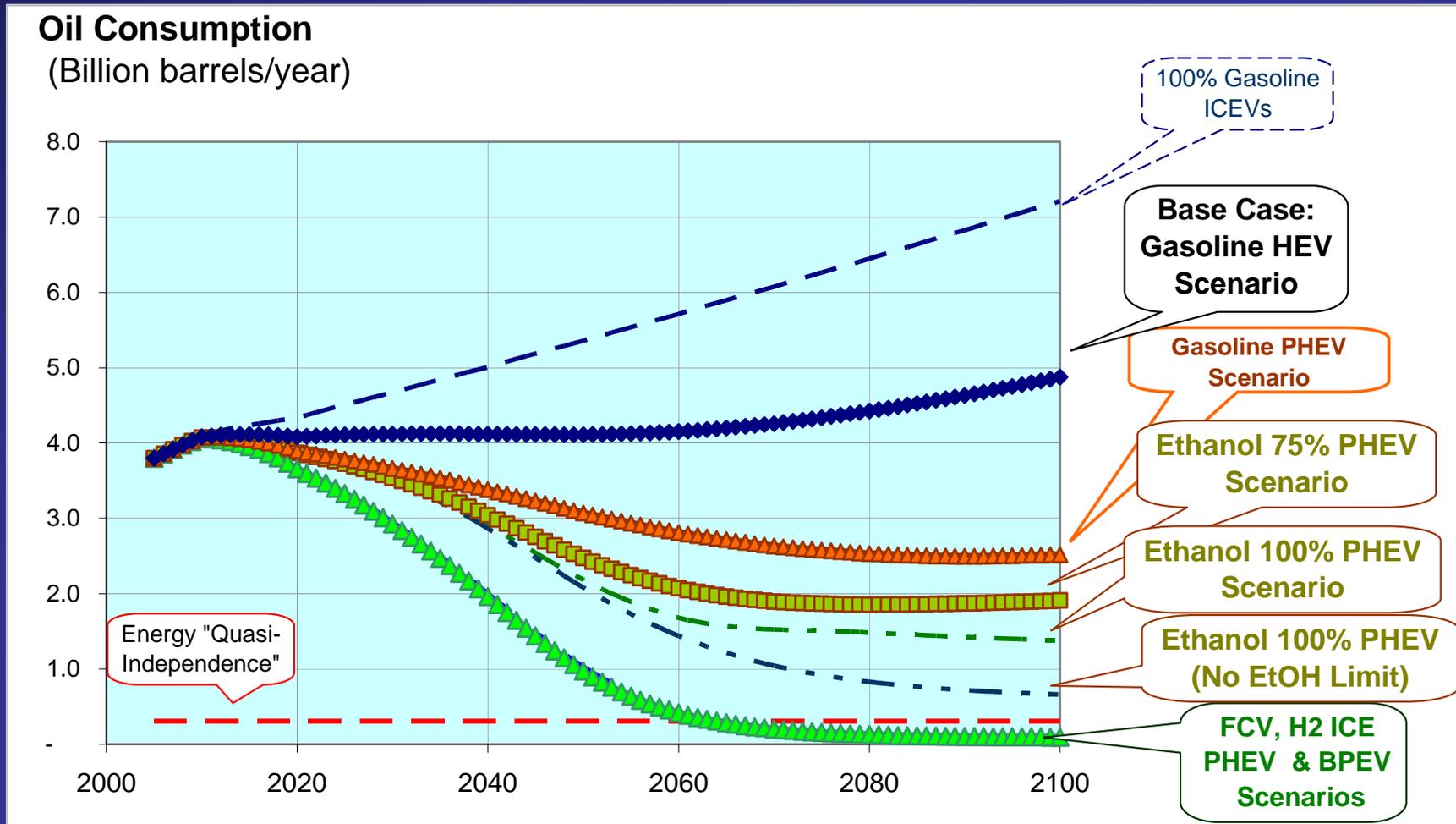
GHG Sensitivity to Hydrogen Source

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



Based on old AEO 2008 data

Oil Consumption Sensitivity to Ethanol Production & Plug-in Capacity



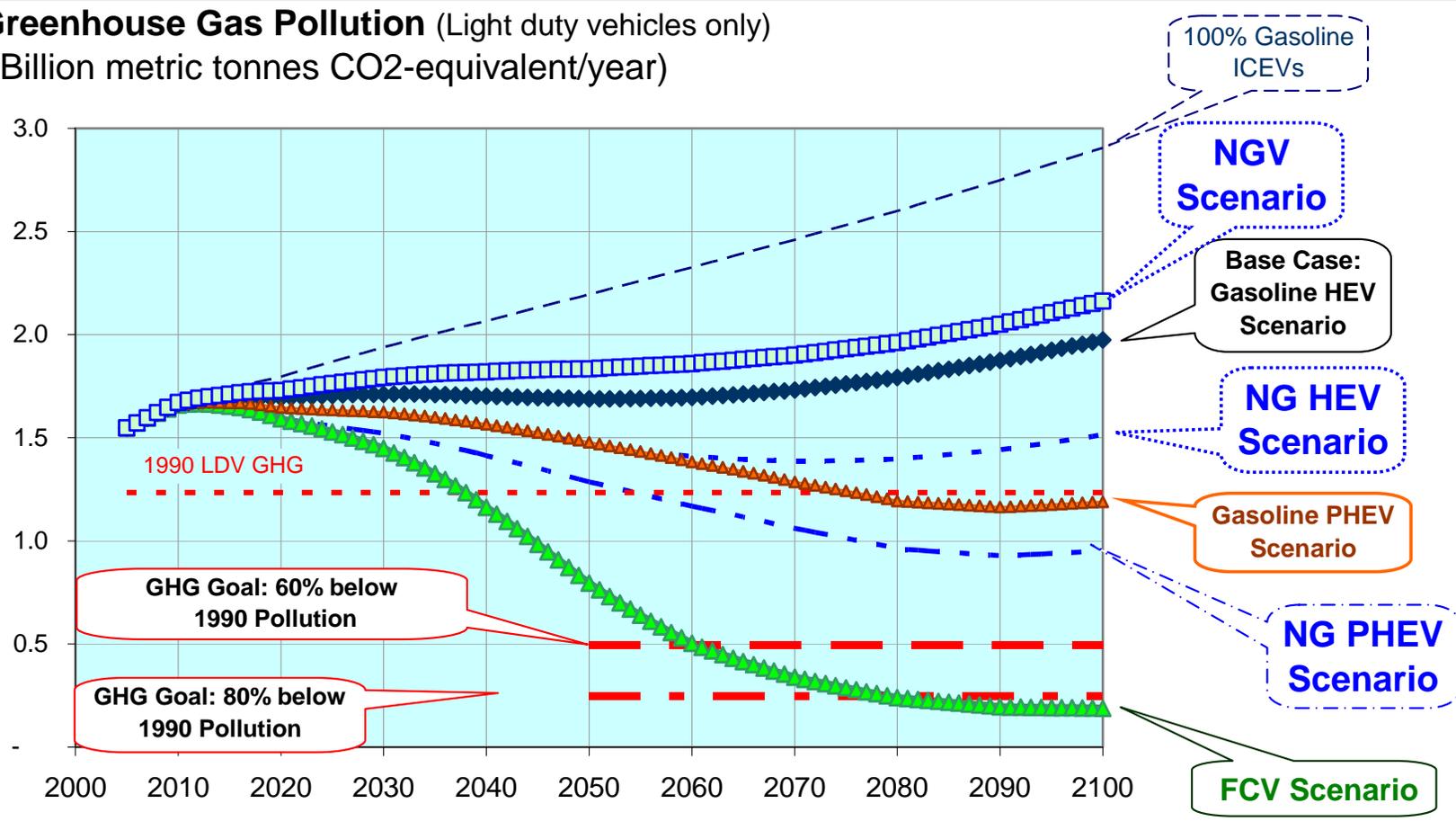
Based on old AEO 2008 data

Backup Slides

- Natural Gas Vehicles
- Diesel CIDI Vehicles

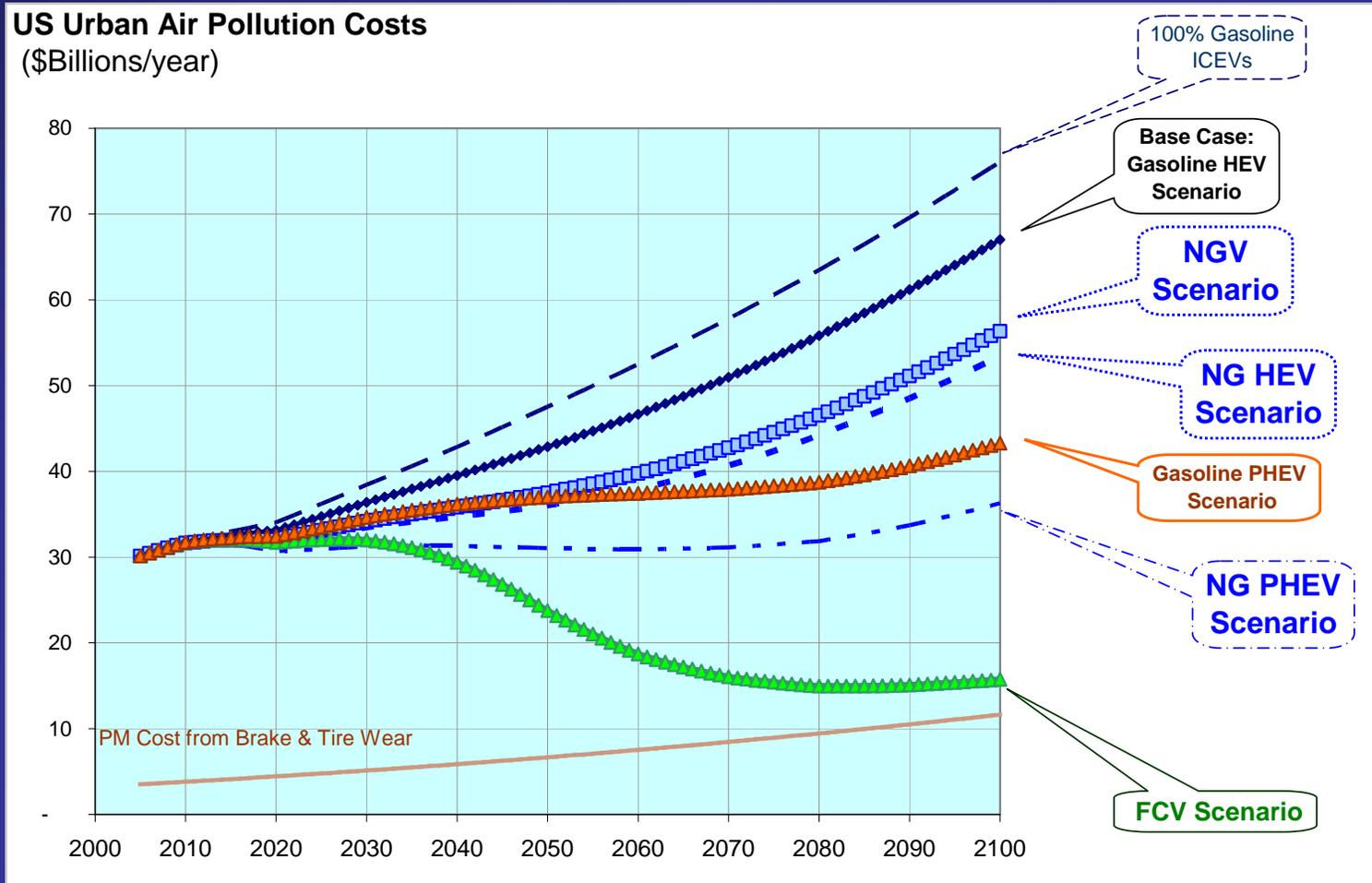
Greenhouse Gases with Natural Gas Vehicles

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



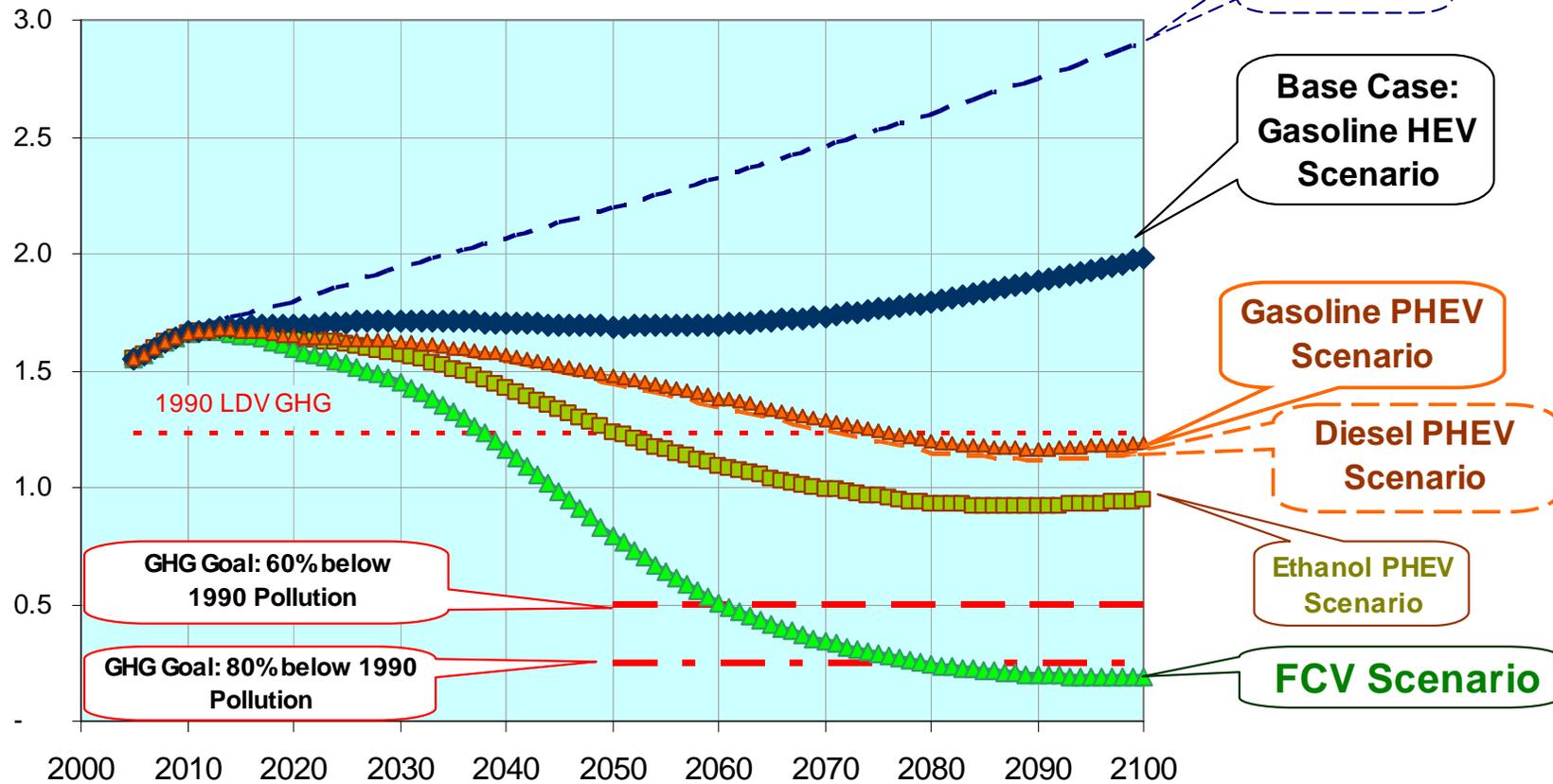
Based on old AEO 2008 data

Urban Air Pollution with Natural Gas Vehicles



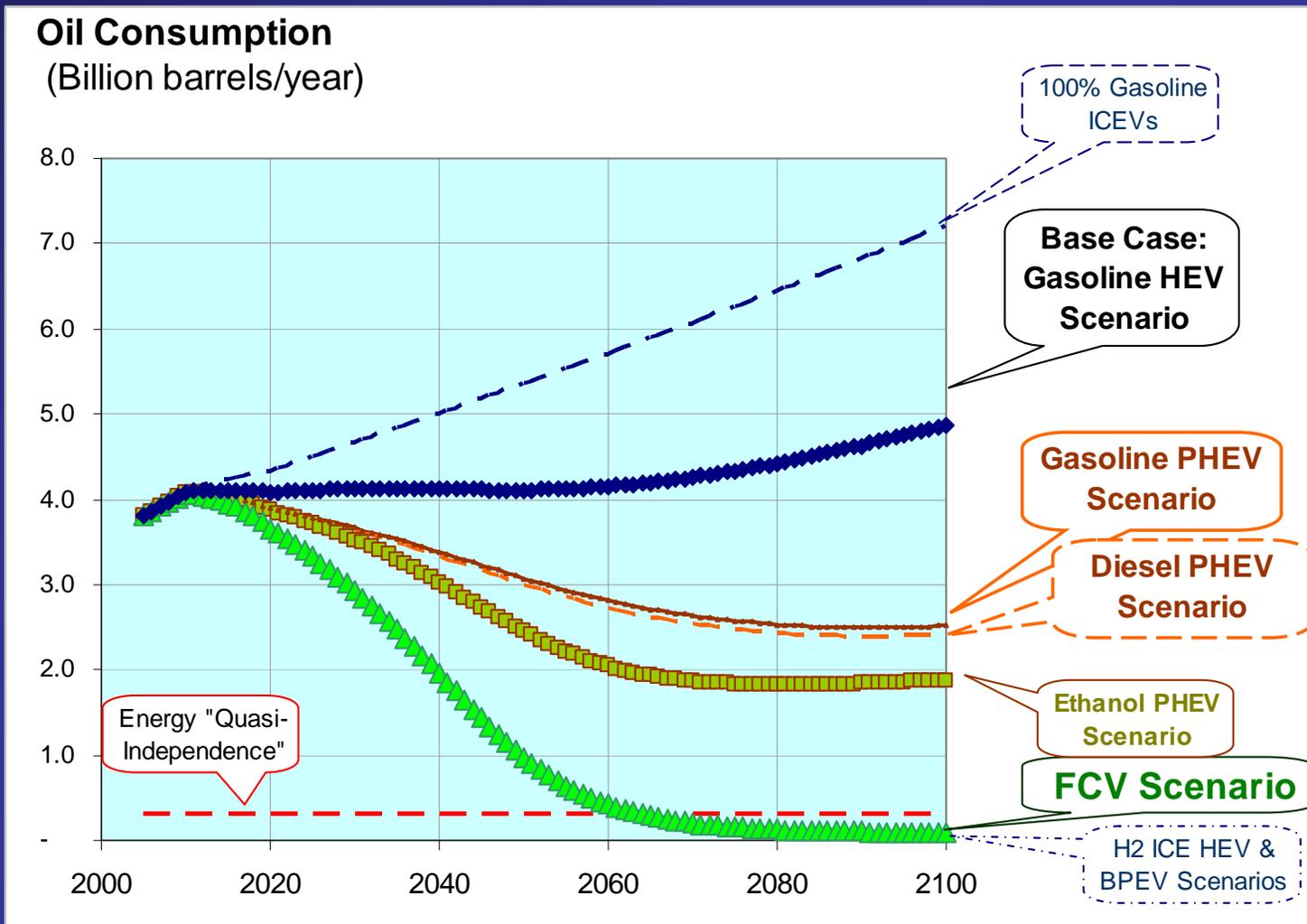
Diesel PHEV GHGs

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



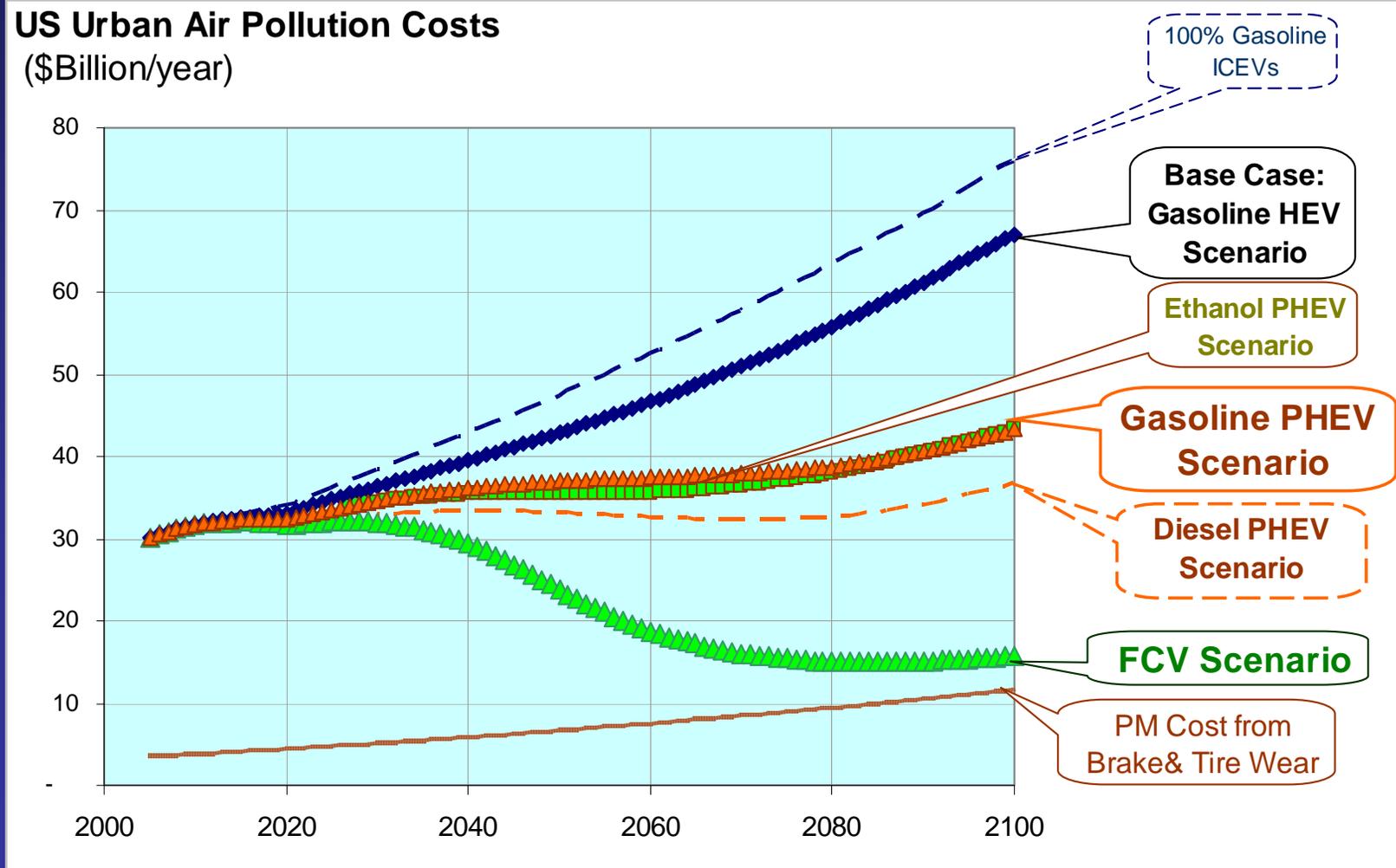
Based on old AEO 2008 data

Diesel PHEV Oil Consumption



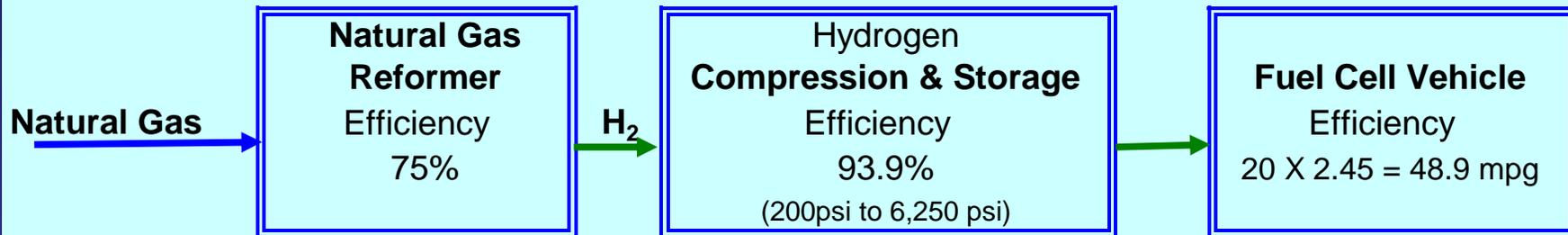
Based on old AEO 2008 data

Diesel PHEV Urban Air Pollution

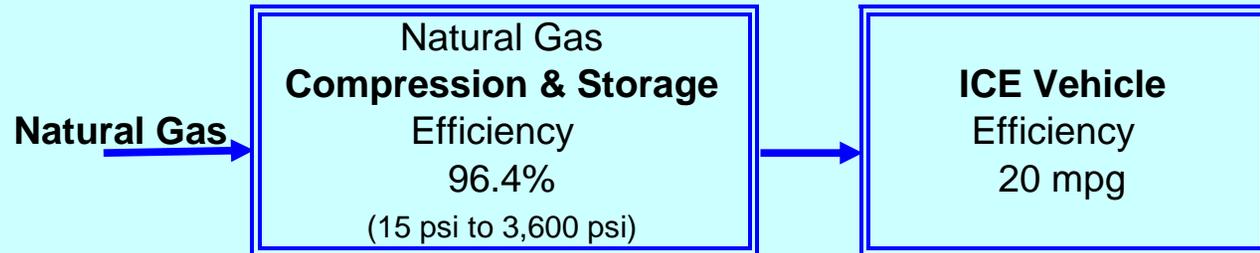


Based on old AEO 2008 data

NGV vs. FCV (Hydrogen from natural gas)



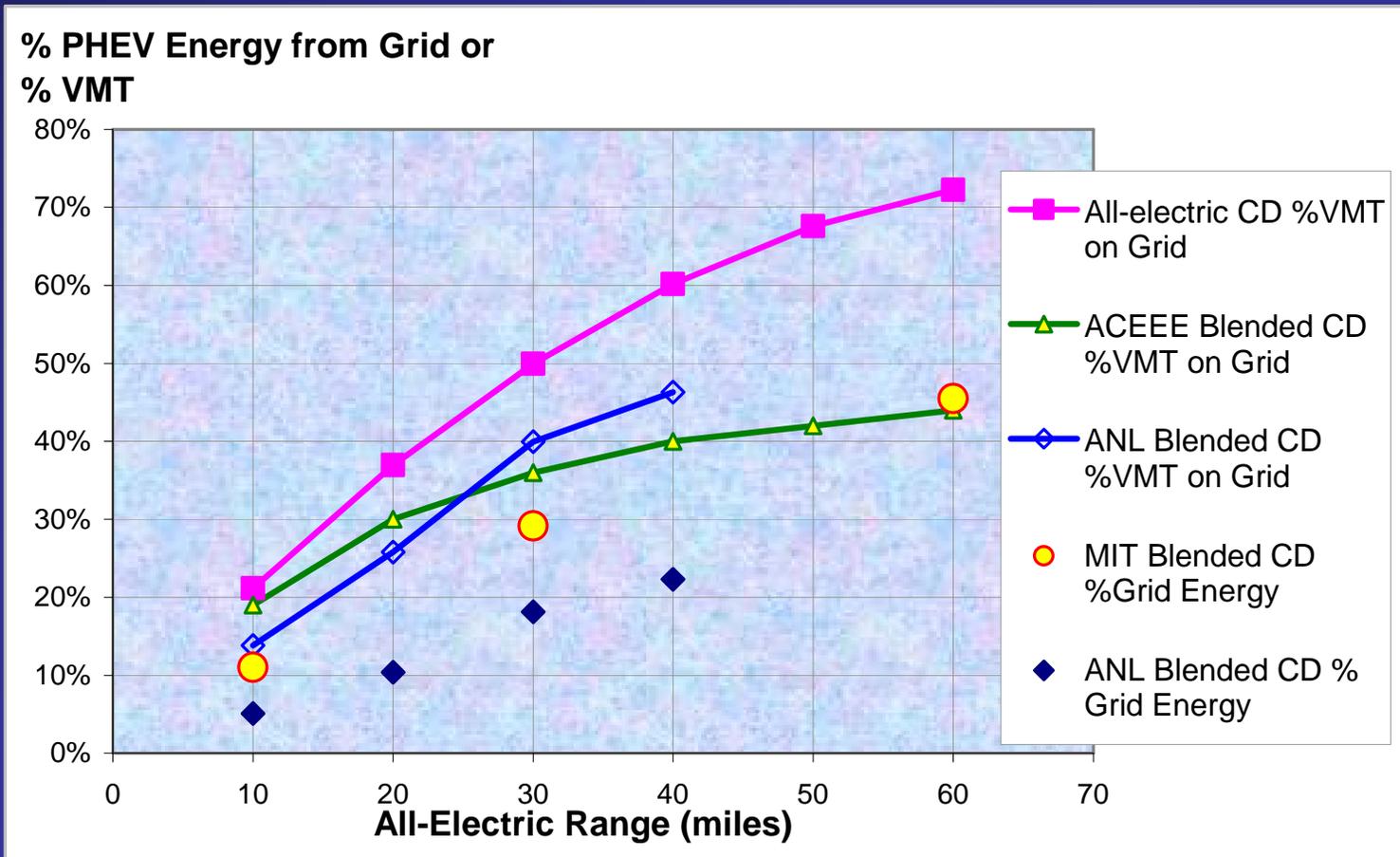
Natural gas efficiency: $0.75 \times 0.939 \times 48.9 = 34.4$



Natural gas efficiency: $0.964 \times 20 = 19.3$

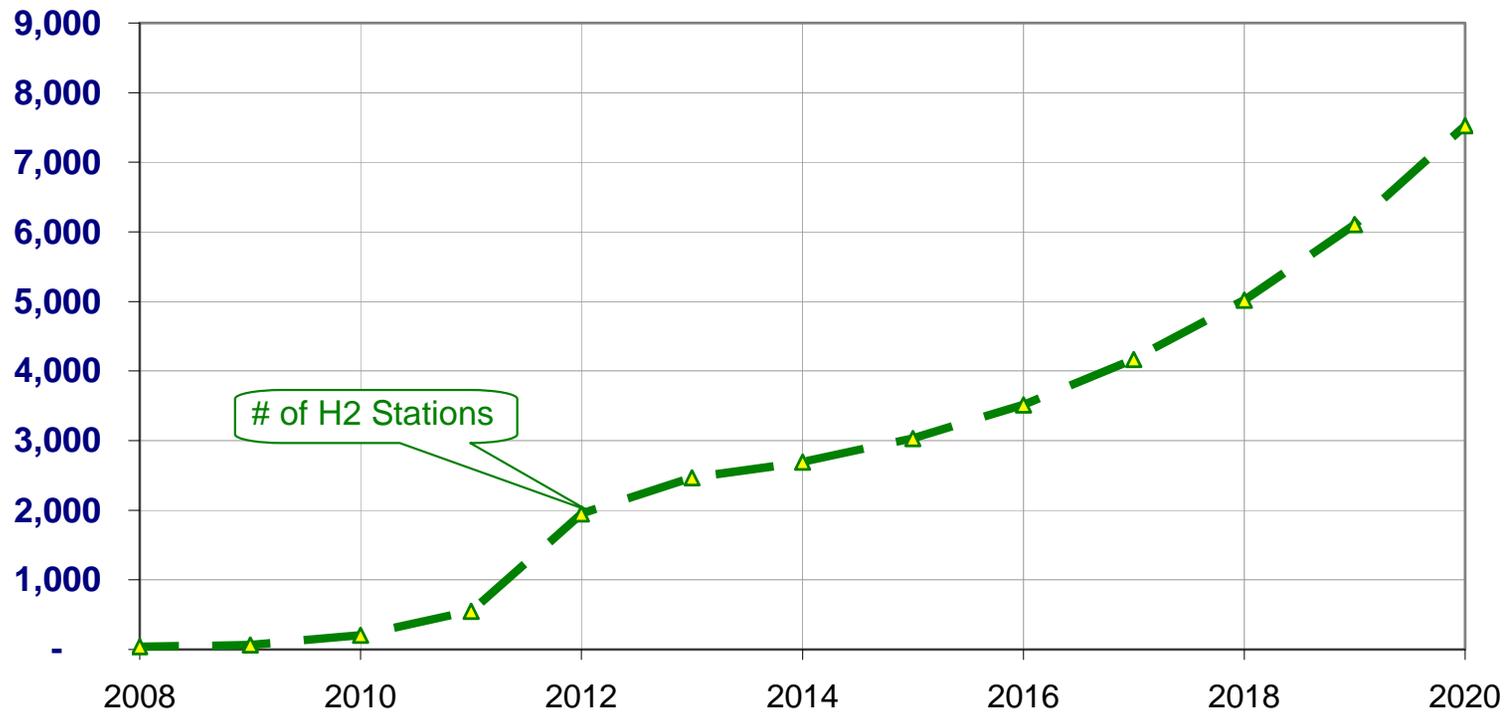
FCV Advantage: 1.79
FCV GHG / ICEV GHG 56% (44% GHG reduction)

Blended Charge Depleting Mode



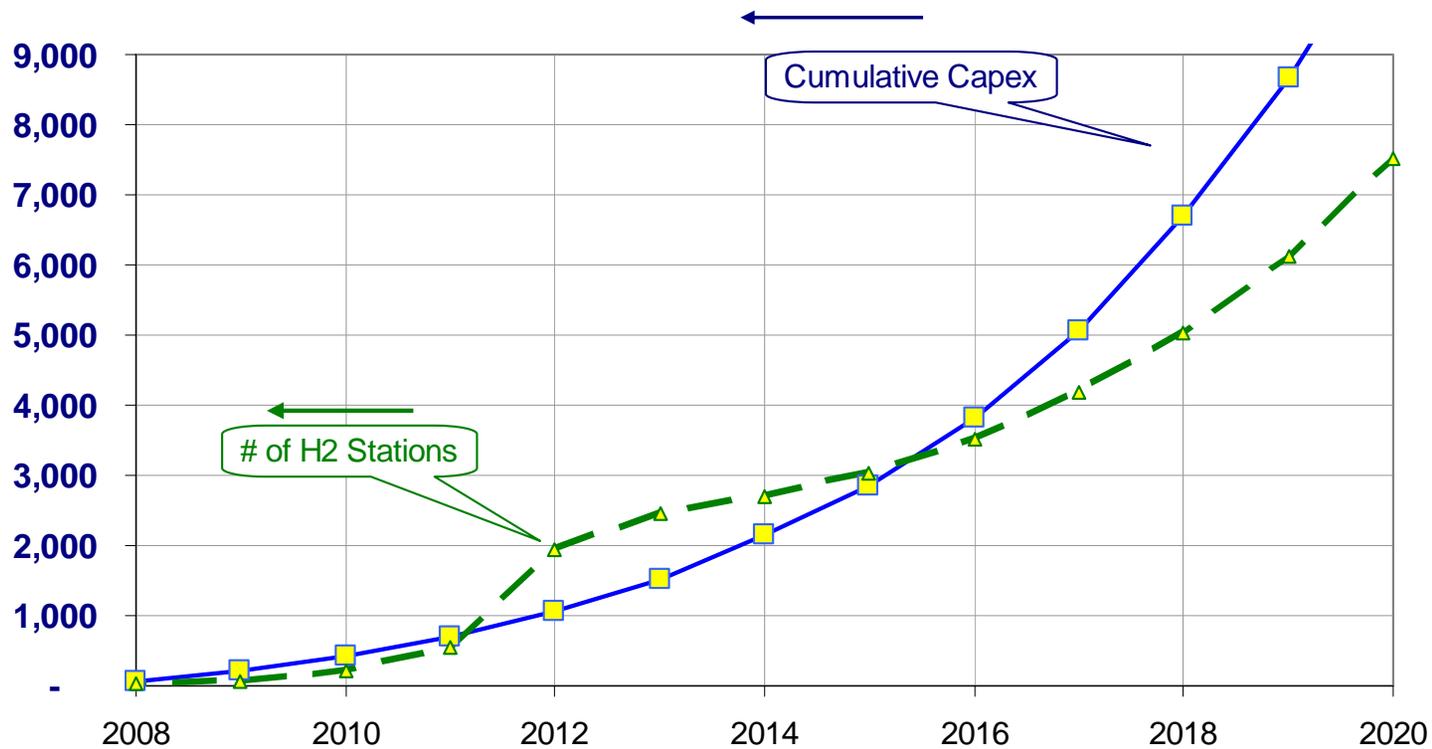
of Hydrogen Stations

of H2 Fueling Stations



Cumulative Capital Expenditures on Hydrogen Fueling Equipment

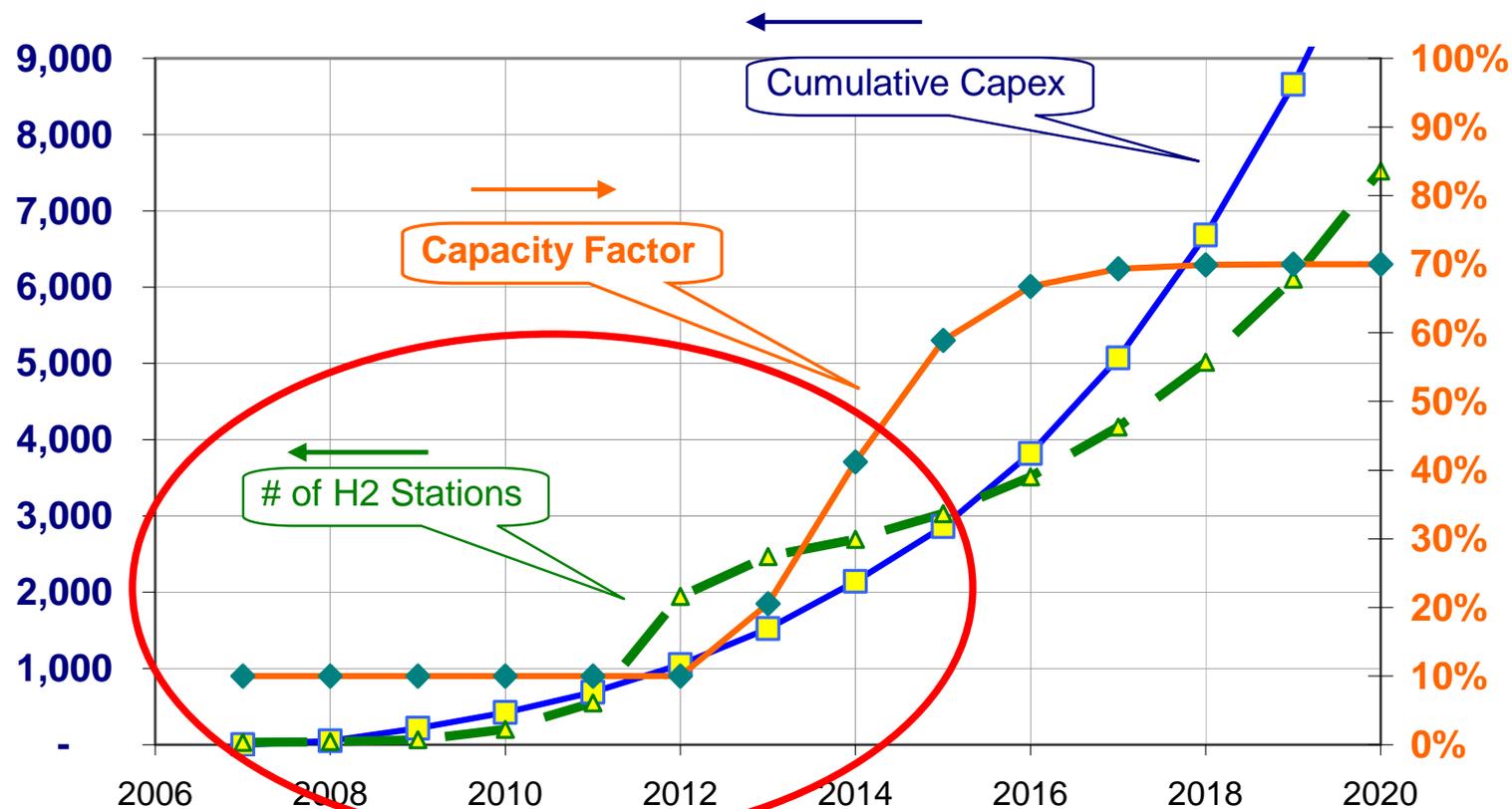
**Cumulative Hydrogen Fueling System
Capital Expenditures
(US\$ millions)
& # of H2 Fueling Stations**



Initial Hydrogen Fueling System Deployments

**Cumulative Hydrogen Fueling System
Capital Expenditures**
(US\$ millions)
& # of H2 Fueling Stations

**Average Capacity
Factor**



HGM 2000: Filling 20 cars or 3 busses / day



Natural Gas

Water

Electricity

Instrument Air



Hydrogen,
Up to 99.99999%
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

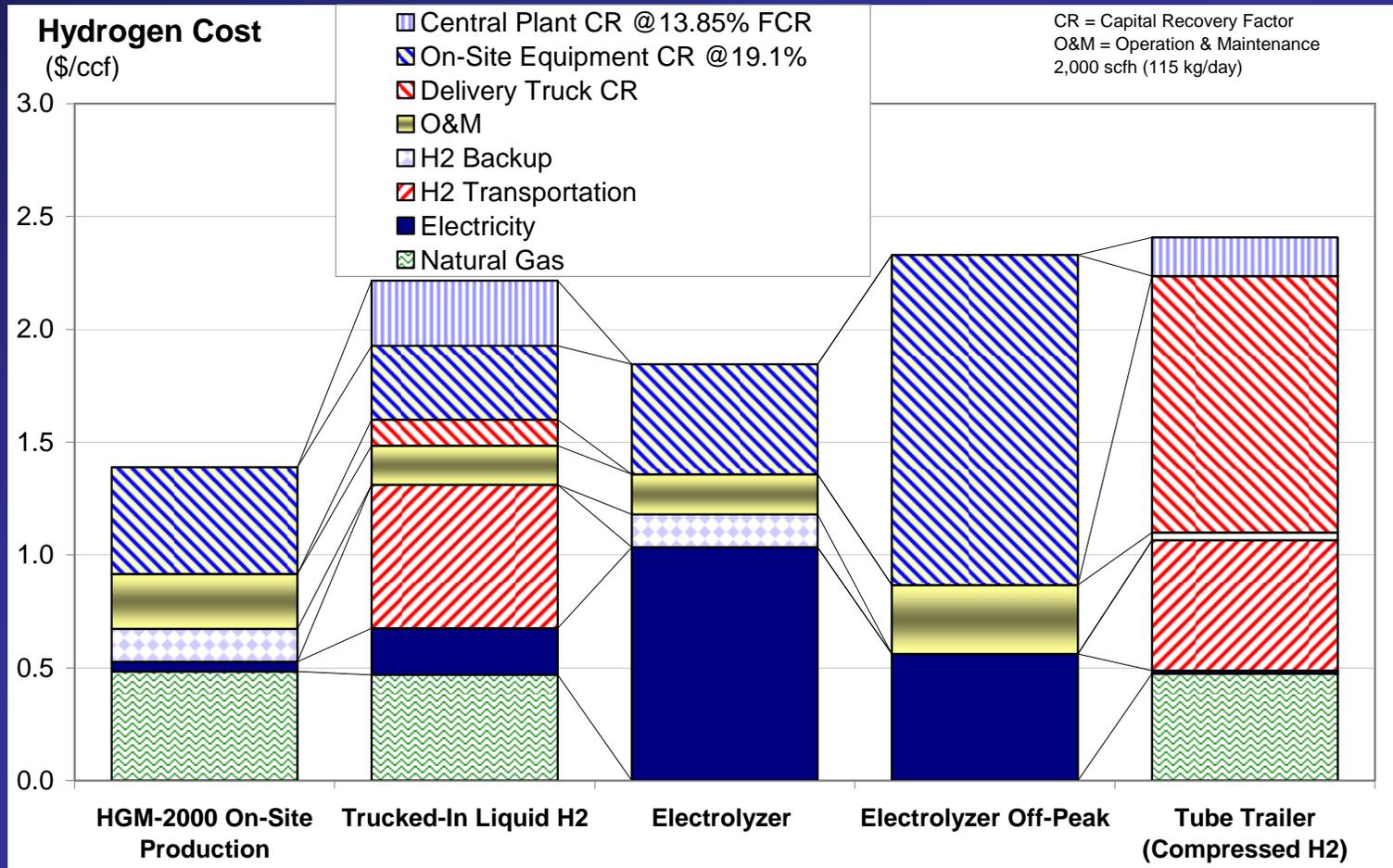


				Hydrogen Cost From On-Site Steam Methane Reformer System (\$/kg)		Hydrogen Cost (\$/gallon of gasoline on a range-equivalent basis, untaxed, relative to ICEV)
	Hydrogen Production Capacity	Equipment Production Quantities	Production Cost	Compression & Storage Cost	Total Cost (\$/kg)	
HGM2k (20 cars/day)	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

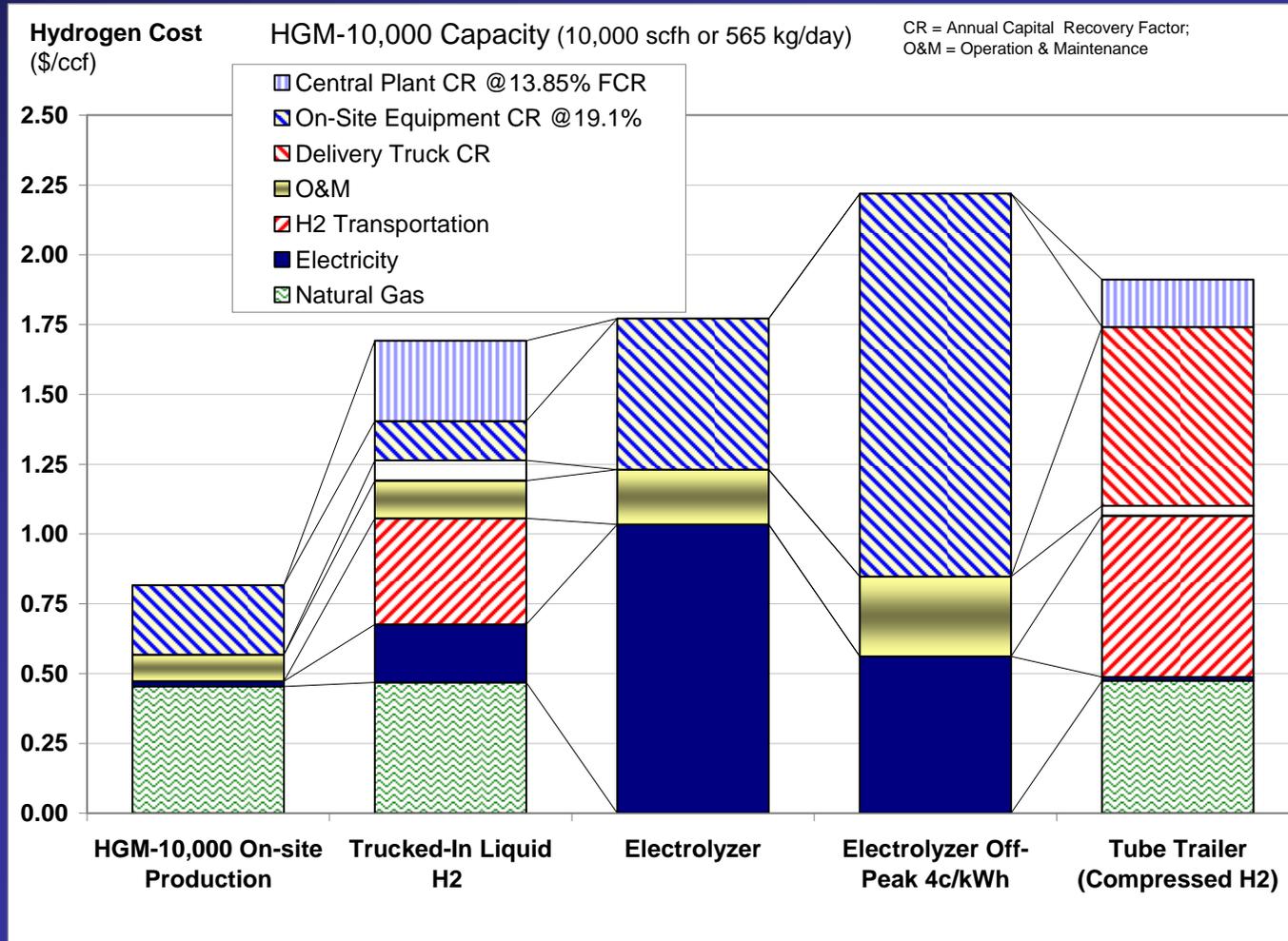
H2 Cost Comparisons (Industrial with HGM-2000)



	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%		

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

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%

H2Gen: markets4.XLS, Tab 'HGM Summary', AE165 - 9/14/2008

H2 Fuel Cost Comparisons

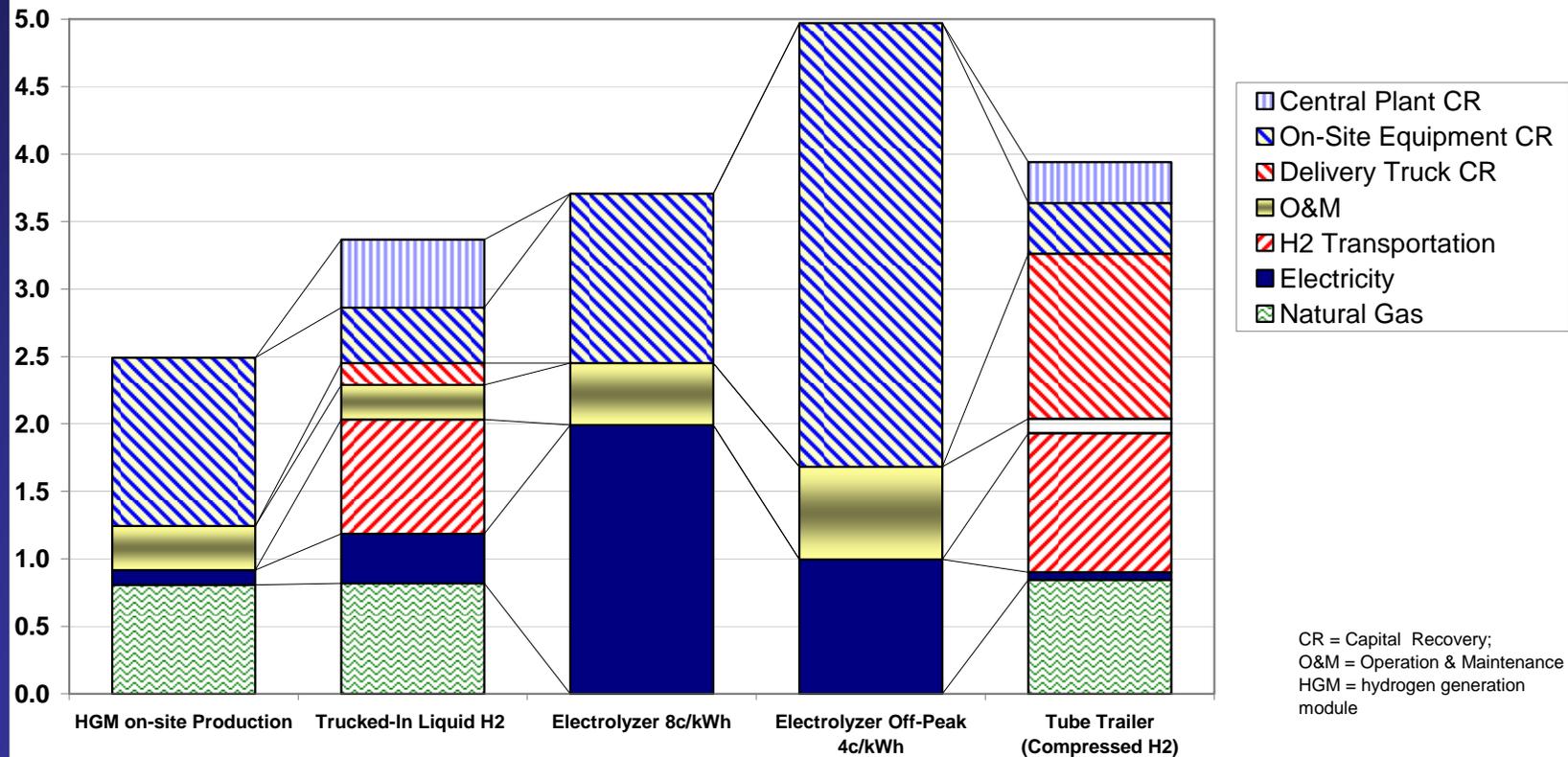


(Hydrogen fuel including compression, storage & dispensing)

Hydrogen Cost

(\$/gallon of gasoline on a range-equivalent basis)*

HGM-10,000 including compression to 7,000 psi, storage & dispensing



CR = Capital Recovery;
O&M = Operation & Maintenance
HGM = hydrogen generation module

* 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

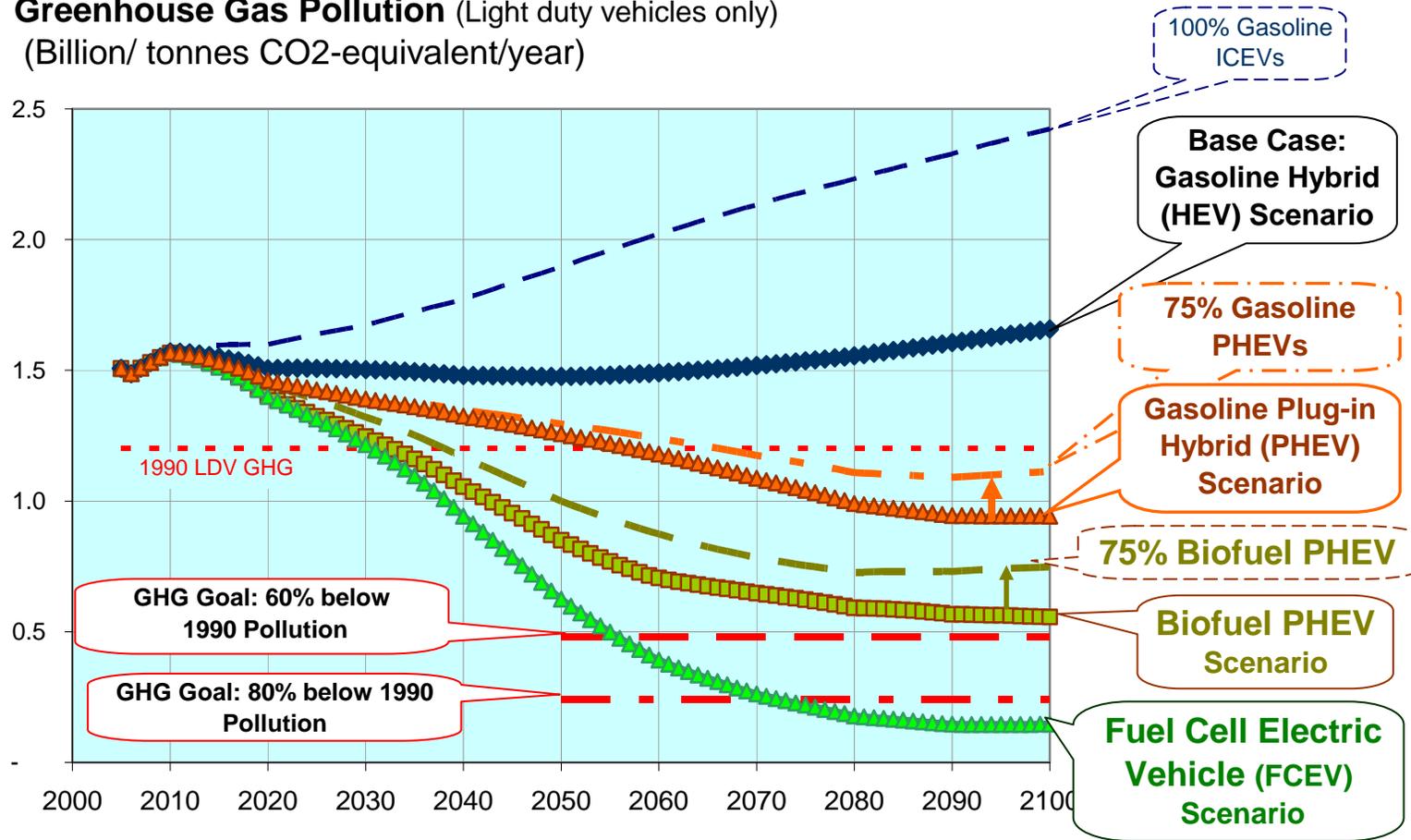
- **Joan Ogden** (1989 Solar Hydrogen Report)
- **Bob Rose, US FC Council** (for many helpful comments & guidance over the years)
- **UC Davis** (Mark Delucchi, et al.)
- **US DOE** (1994 Ford/DOE/DTI to present; H2A cost model, Steve Chalk, JoAnn Milliken, et al.)
- **Argonne National Lab** (Michael Wang & GREET model)
- **NHA hydrogen story task force** (Frank Novachek, leader, John Elter – Stationary applications)
- **Barney Rush** (CEO H₂Gen)

GHG: 75% Cap on PHEVs

(Due to limited night-time access to outlets)

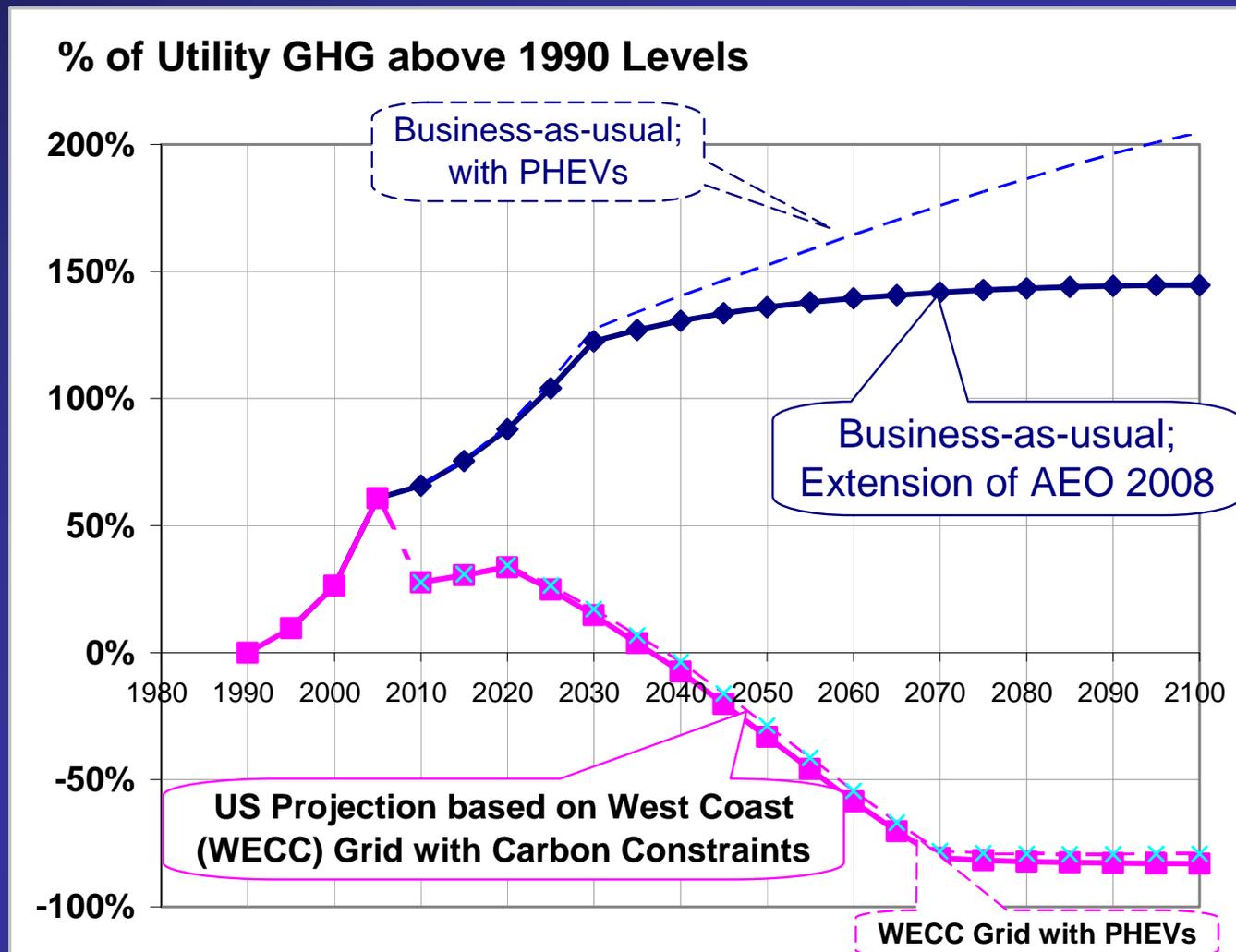


Greenhouse Gas Pollution (Light duty vehicles only)
(Billion/ tonnes CO₂-equivalent/year)

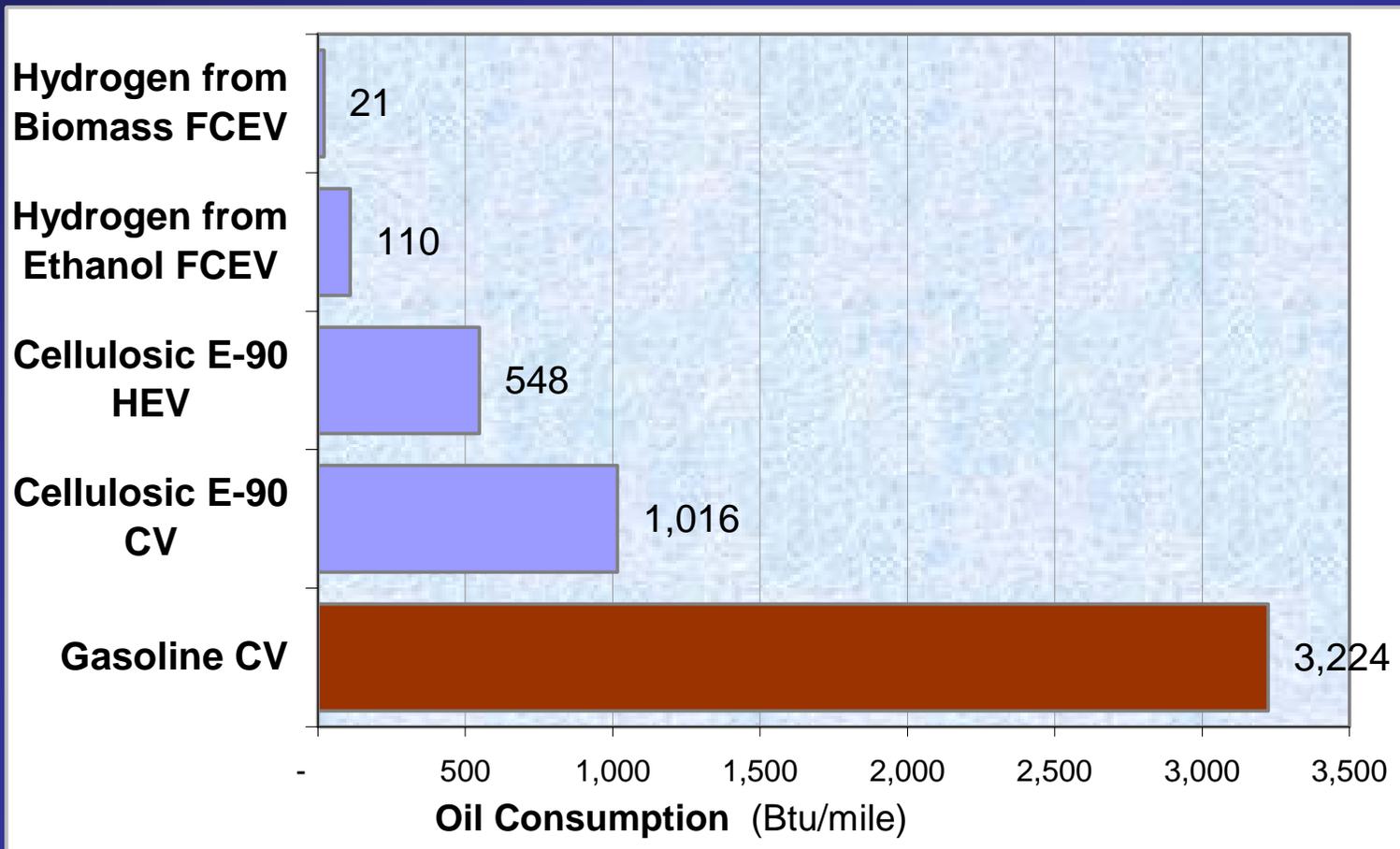


Story Simultaneous.XLS, Tab 'Graphs', Q 494 3/4/2009

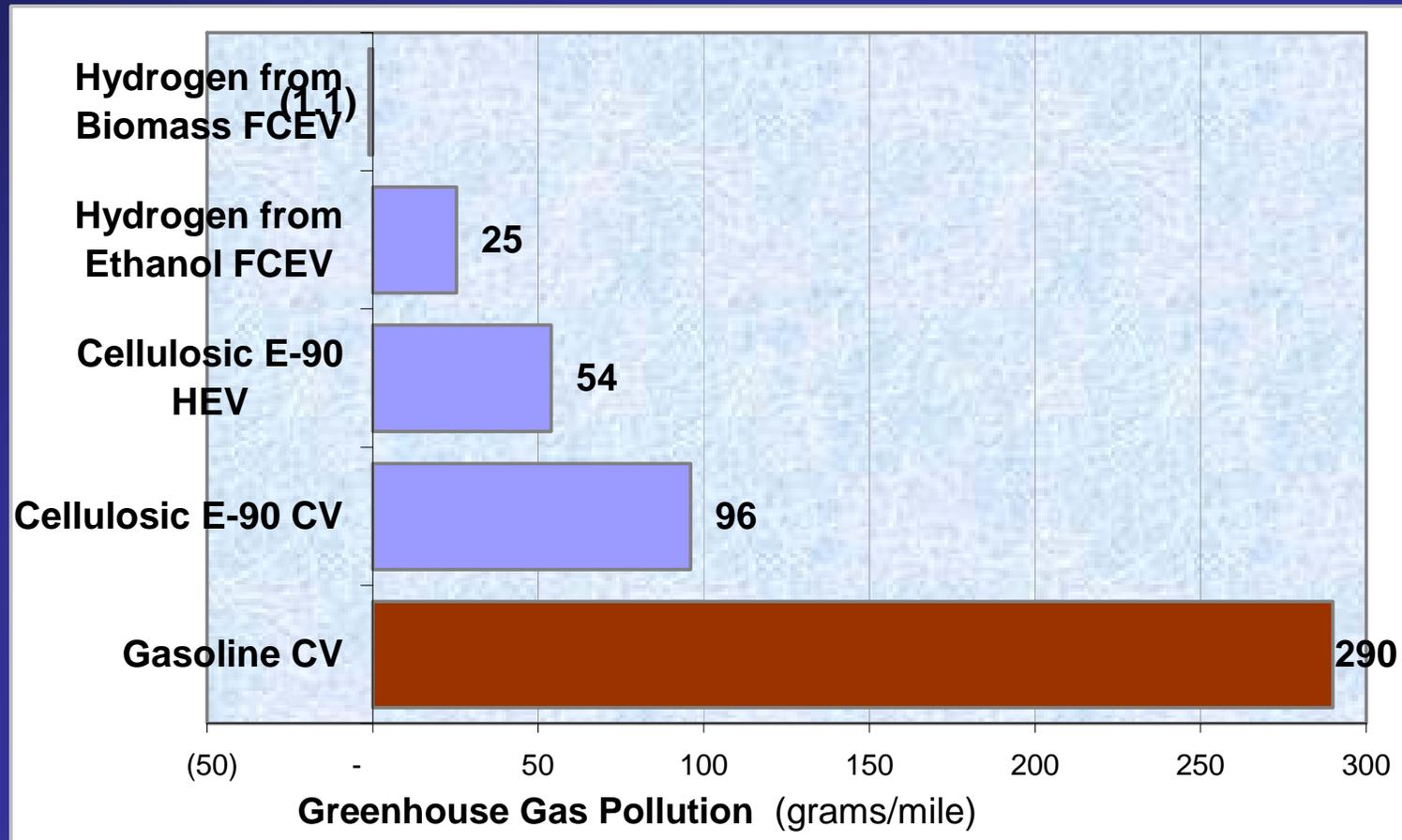
Grid GHGs Relative to 1990



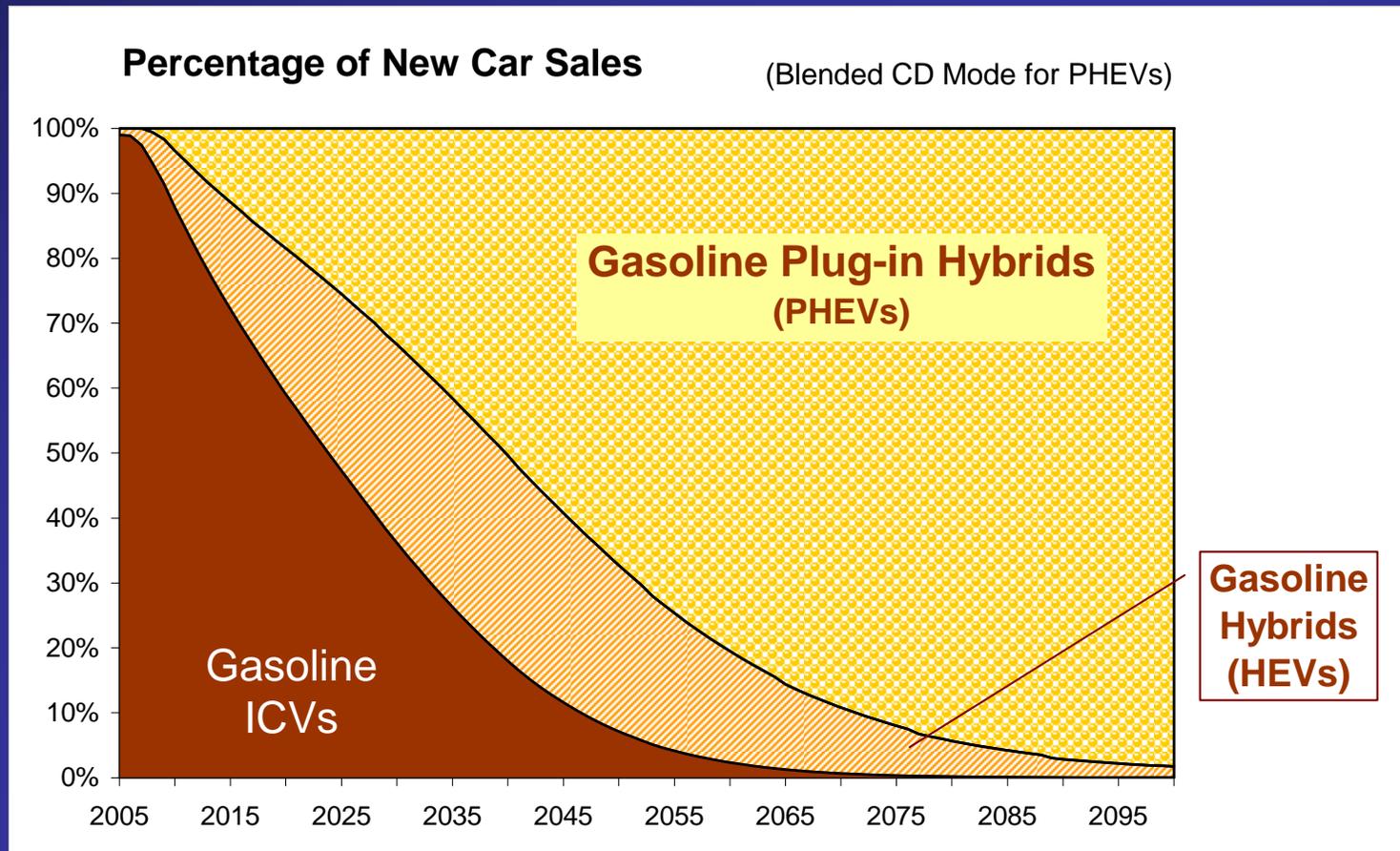
Hydrogen from Ethanol & Biomass: Oil Consumption Comparison



Hydrogen from Ethanol & Biomass: Greenhouse Gas Comparisons



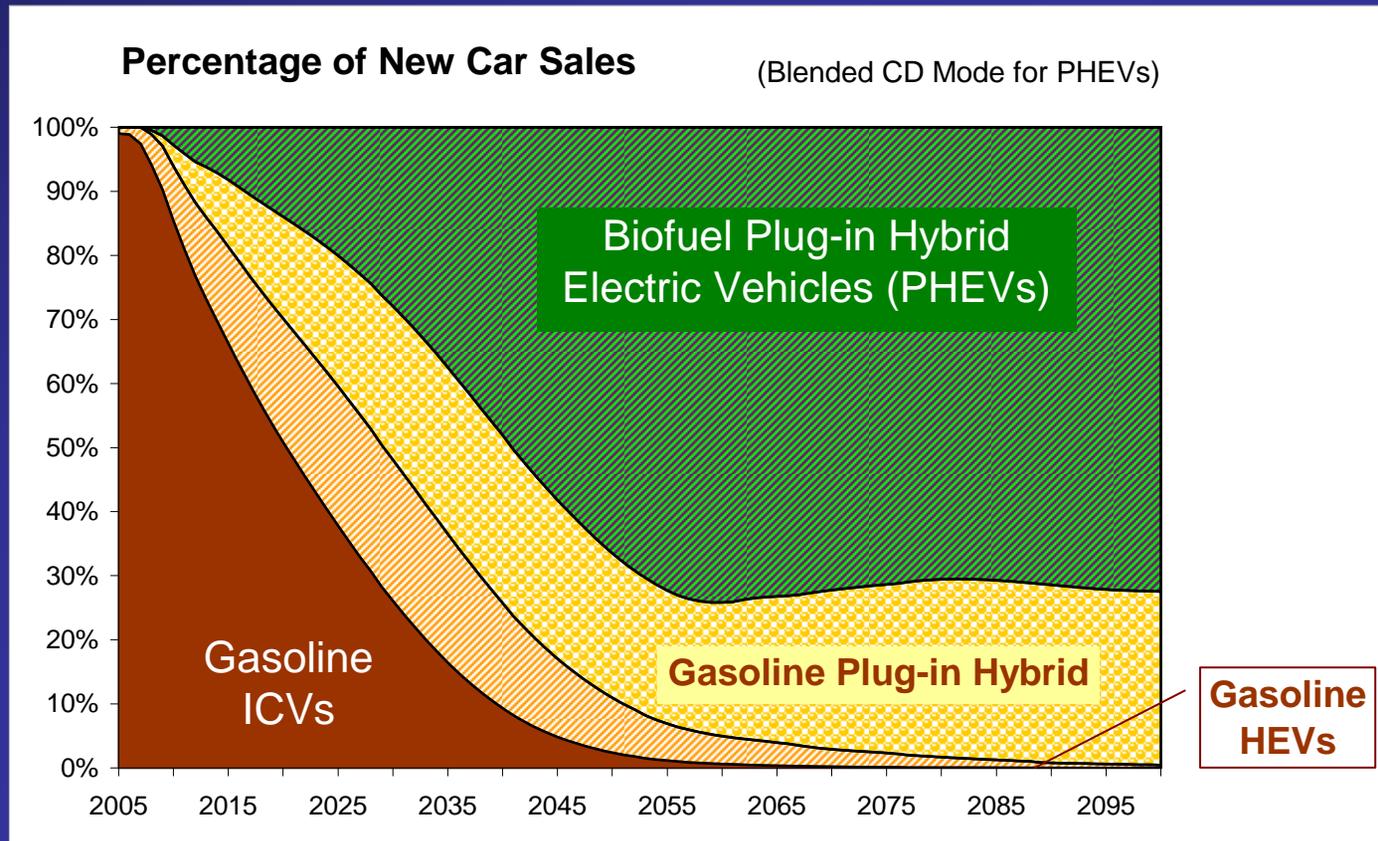
100% Gasoline Plug-In ICE Hybrid Electric Vehicle (PHEV) Scenario Market Shares



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

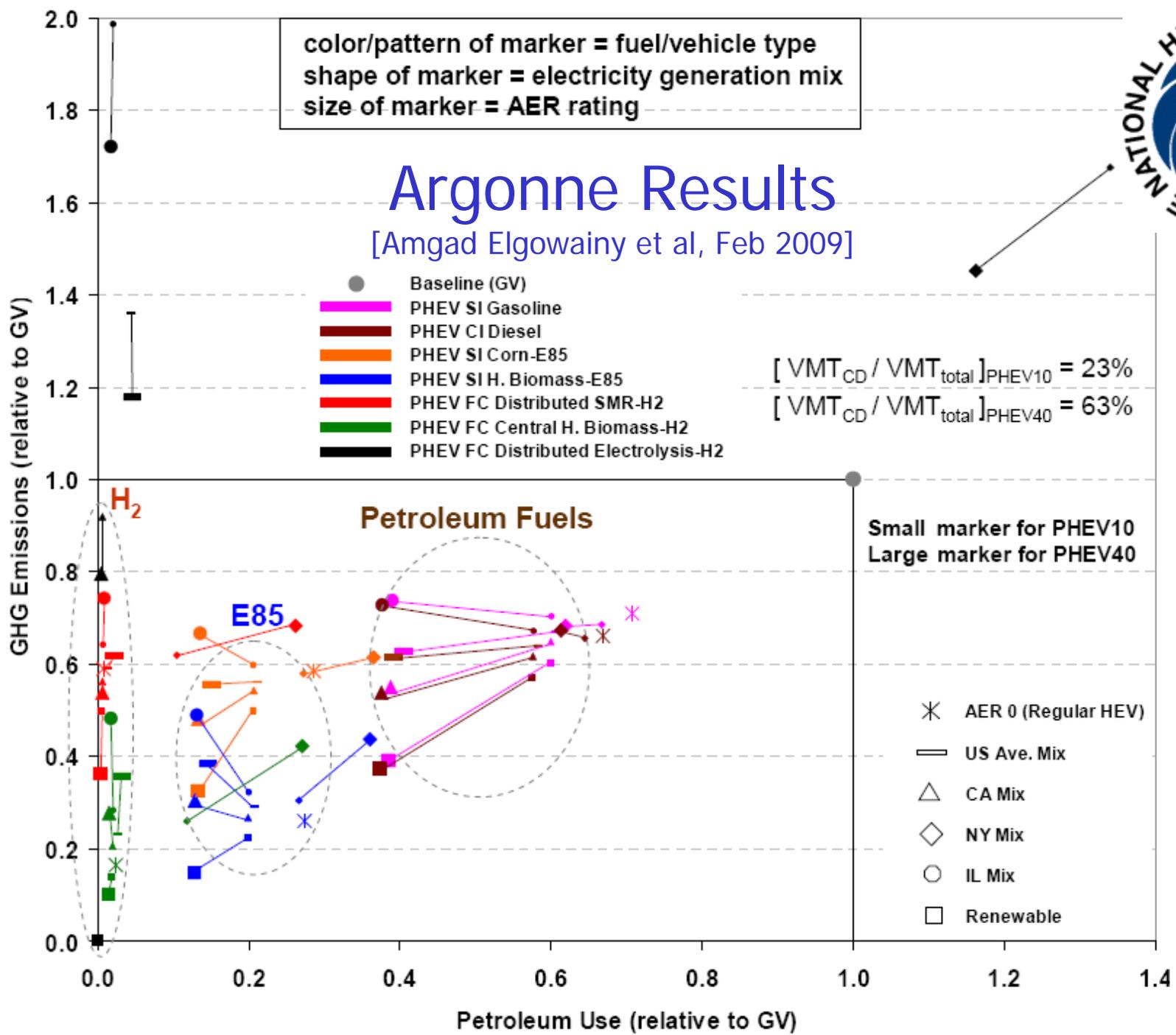
X = primary fuel; S = secondary fuel; ICEV = internal combustion engine vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; FC = fuel cell; BEV = battery-powered electric vehicle



Argonne Results

[Amgad Elgowainy et al, Feb 2009]

color/pattern of marker = fuel/vehicle type
 shape of marker = electricity generation mix
 size of marker = AER rating





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

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!