Making the Case for Hydrogen and Fuel Cell Electric Vehicles

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Alternative Vehicles

- Hybrid electric vehicles (HEVs)
- Plug-in hybrid electric vehicles (PHEVs)
- Biofuel/ethanol PHEVs
- Battery electric vehicles (BEVs)
- Fuel Cell electric vehicles (FCEVs)

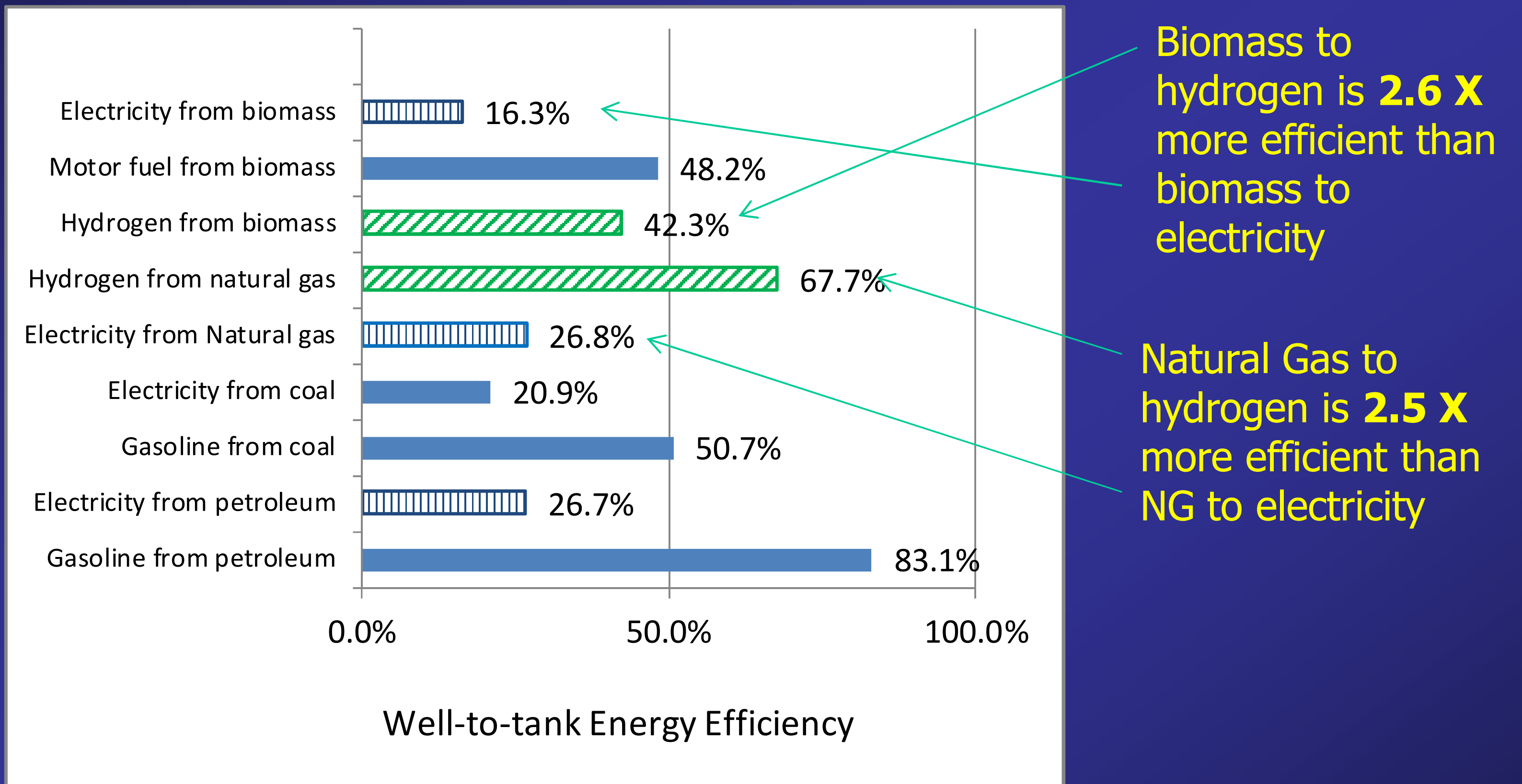
Outline

- 1. Fuel production Efficiencies
- 2. Vehicle & Fuel Attributes
  - **Vehicle Cost: Total life cycle cost (LCC) or total cost of ownership (TCO)**
  - **Fuel infrastructure cost**
- **3.** Environmental and Energy Security Attributes
  - **Market Penetration Potential**
    - **BEV size and range limitations**
    - **BEV Sales Potential in US**
  - **Greenhouse gas (GHG) emissions**
  - **Local air pollution**
  - **Oil Consumption**
- 4. Natural Gas Utilization
- 5. Market Acceptance Test

Fuel Production Efficiencies

- Doesn't it take more energy to make hydrogen than is contained in that hydrogen?
- Yes,
- But that is true of most fuels →

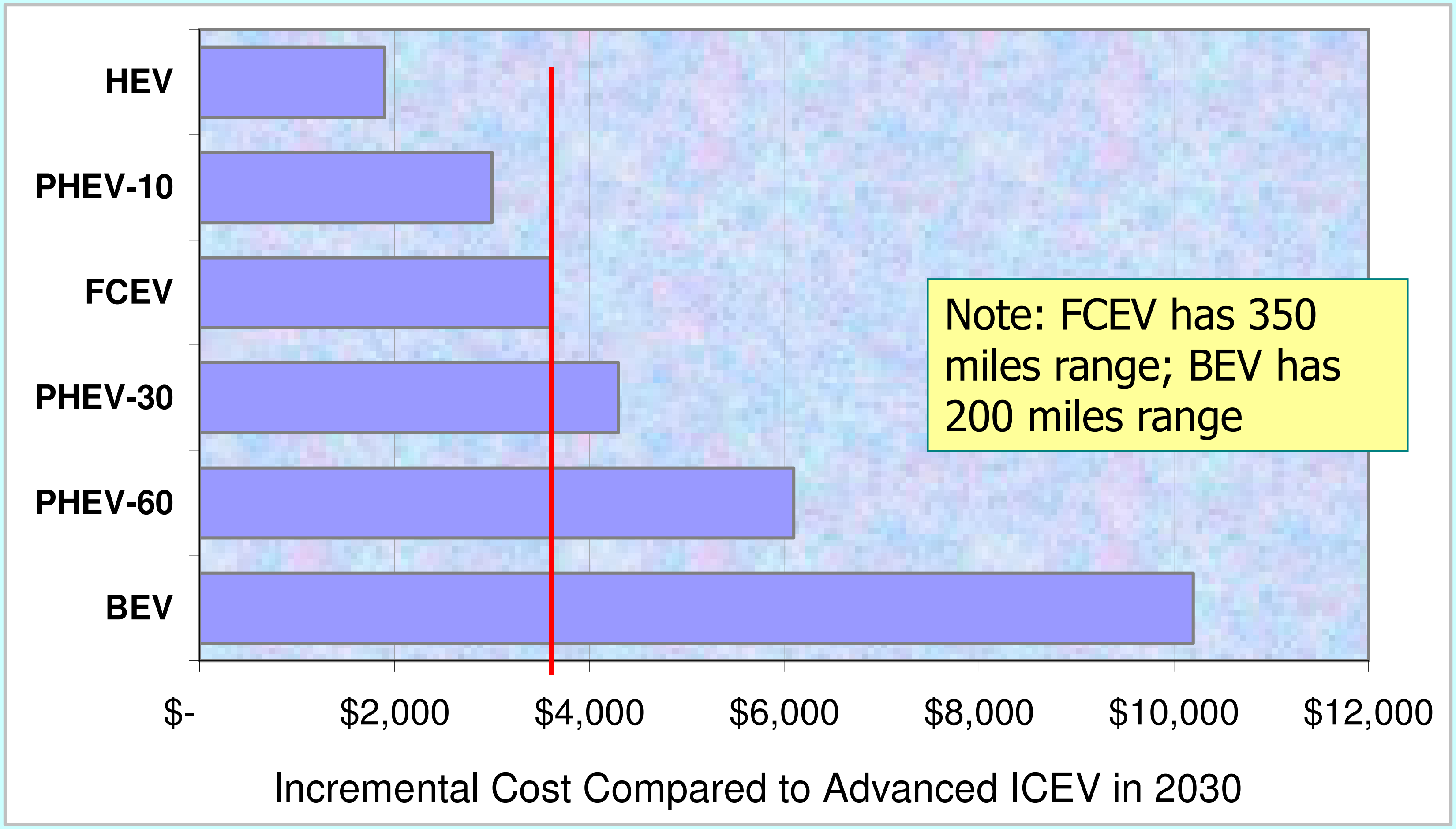
Fuel Production Efficiencies



work/hydrogen/J46 of fuel production.XLS; H49 - 10 / 11 / 2011

Primary source: Quanlu Wang and Daniel Sperling,"Energy-Production chains estimated for 1995," "Energy impacts of using electric vehicles in Southern California," Institute of Transportation Studies, UCD-ITS-RR-92-13, May 1992.
Hydrogen from biomass: P. Spath et al., Biomass to hydrogen production detailed design and economics utilizing the Batelle Columbus Laboratory indirectly-heated gasifier, NREL/TP-510-37409, May 2005, page 30:

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



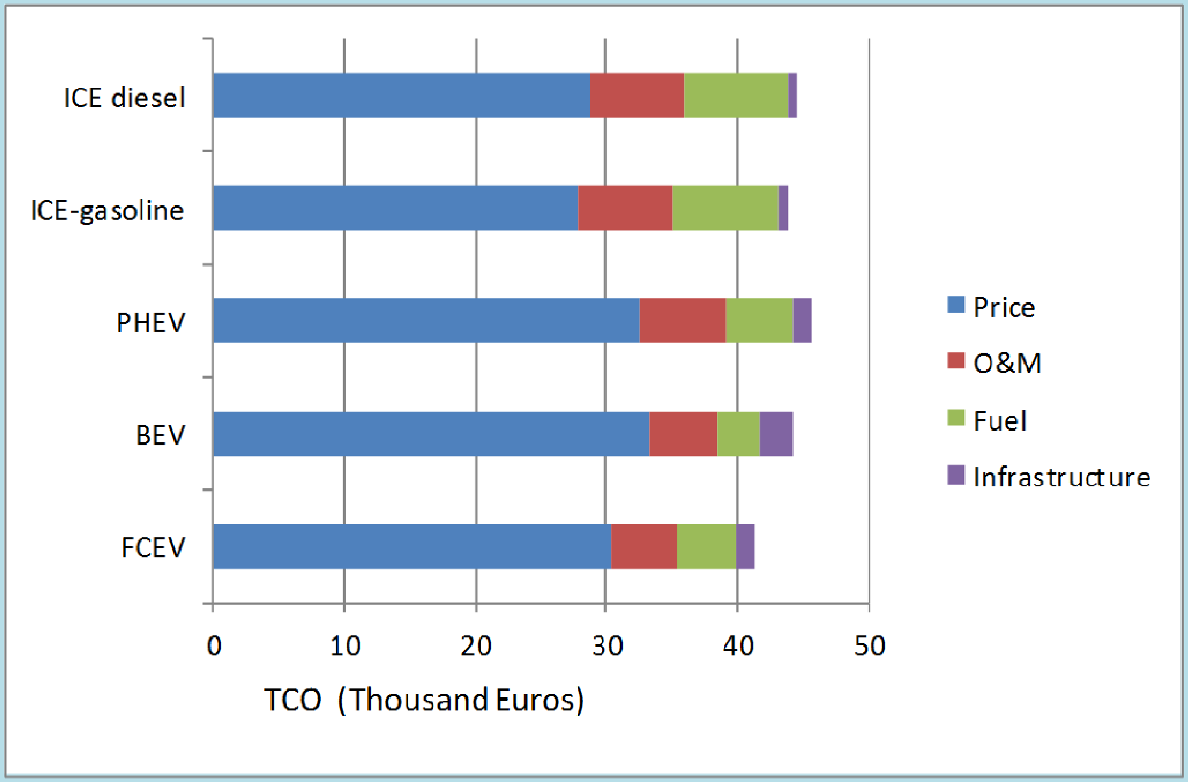
Ref: Kromer & Heywood, "Electric Powertrains: Opportunities & Challenges in the U.S. Light-Duty Vehicle Fleet Report # LFEE 2007-03RP, MIT, May, 2007, Table 53

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

McKinsey & Company 2007 EU Report

available at:
http://www.europeanclimate.org/documents/Power_trains_for_Europe.pdf

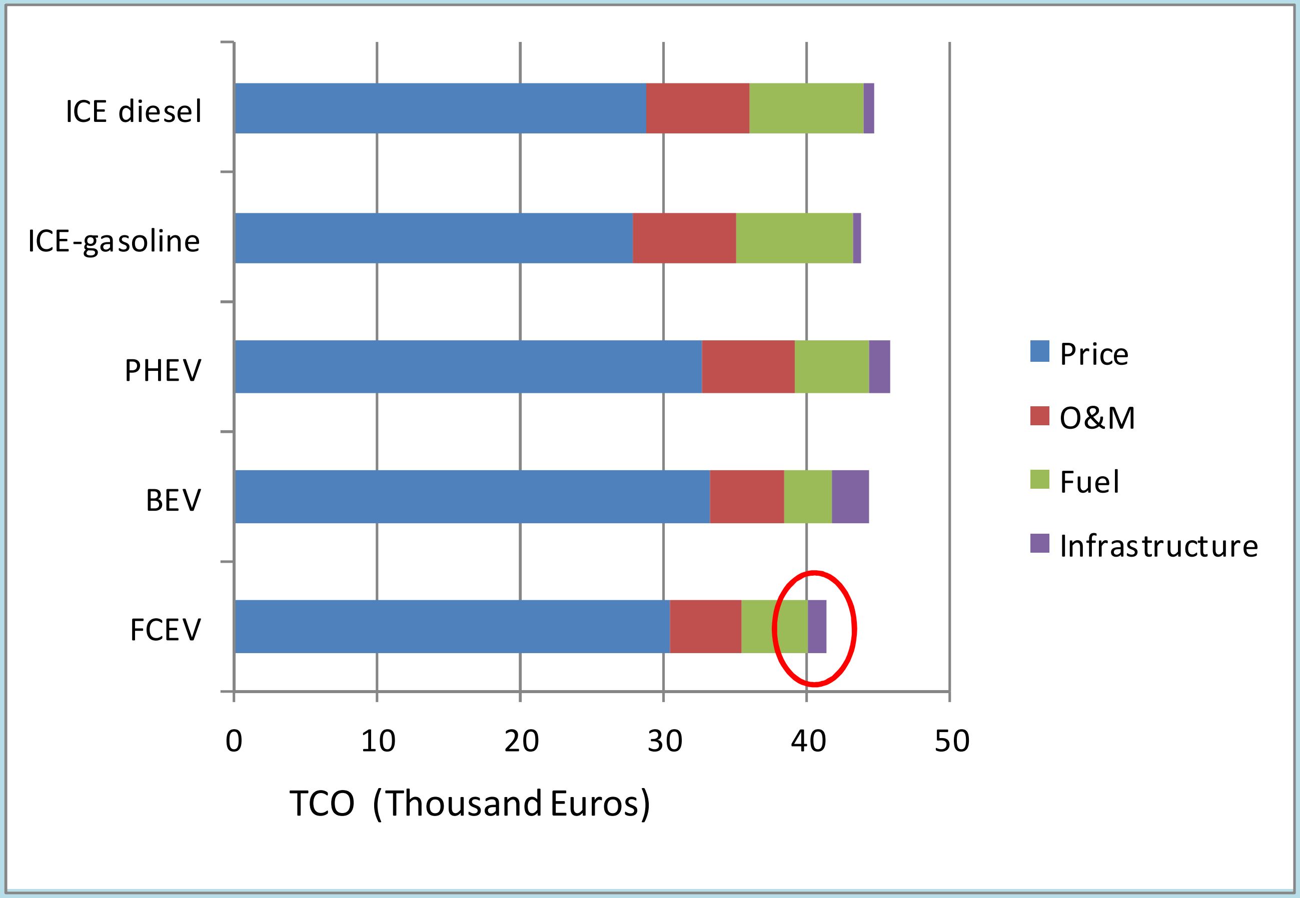
J-Segment (SUV) total cost of ownership in 2030 (McKinsey-EU)



McKinsey EU Data.xls; Tab 'Detaila'; X94 5/6/2011

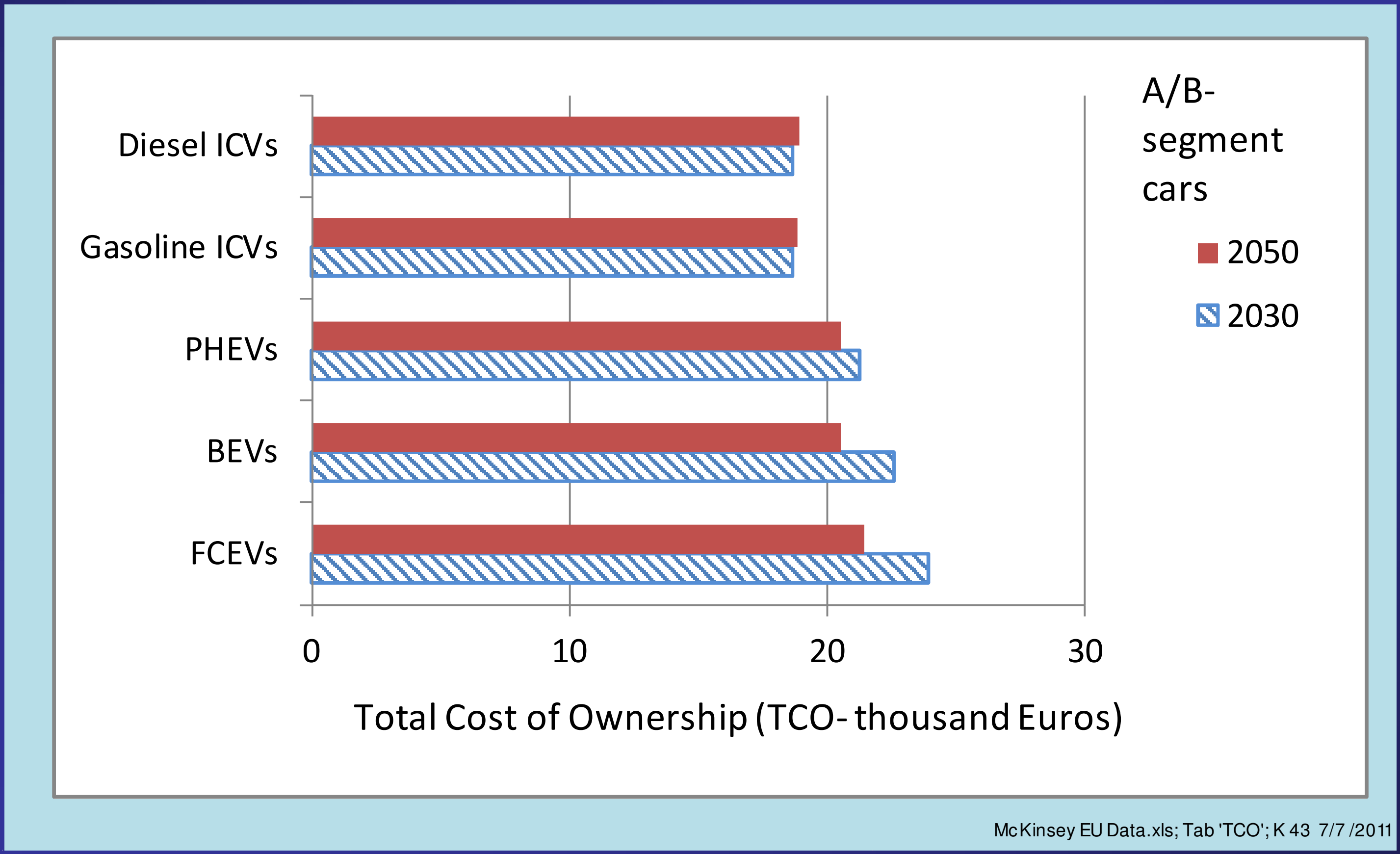
available at: http://www.europeanclimate.org/documents/Power_trains_for_Europe.pdf

J-Segment (SUV) total cost of ownership in 2050 (McKinsey)



McKinsey EU Data.xls; Tab 'Detaila'; X92 2/2/2011

A/B-Segment (small cars) total cost of ownership (McKinsey)



Fuel Infrastructure Costs

Hydrogen Infrastructure Cost

Station Type	kg/day	FCEVs supported	Installed Cost($M)	Cost per FCEV & total cost for 1 M FCEVs ($M)	Average $/FCEV	
Mobile refueler	10	21	0.243	$ 11,571		
SMR	100	211	1.048	$ 4,967		
SMR	113	238	1.078	$ 4,529		
SMR	480	1,014	2.740	$ 2,702		
SMR	565	1,193	3.088	$ 2,588	$ 3,201	$ 4,038
SMR	1000	2,112	5.137	$ 2,432		
LH2 station	1000	2,112	2.697	$ 1,277		
HTFC energy station	91	192	1.345	$ 7,005		
DOE-H2A-SMR	1500	3,169	4.71	$ 1,486		
Current-NRC/NAS-SMR	480	1,014	1.848	$ 1,822		
Future-UC-Davis SMR	480	1,014	1.458	$ 1,438	$ 1,191	
Future-NRC/NAS	480	1,014	0.957	$ 944		

BEVs outlet cost, charging times.XLS; WS 'H2 cost per car' N 22 5/2 /2011

Primary source: Jonathan S. Weinert & Timothy E. Lipman, "An Assessment of the Near-Term Costs of Hydrogen refueling stations and station components," Institute for Transportation Studies, U. of California at Davis, Final Report # UCD-ITS-RR-06-03, January 13, 2006

SMR = Steam methane reformer (method of converting natural gas to hydrogen)

Hydrogen infrastructure cost per vehicle

- Average cost initially: $3,200/FCEV
- Future cost estimate: $1,200/FCEV

Electrical Infrastructure Costs

Type II (240V) charging required

			Charging time (hours)		
	Nominal AER range (miles)	EPA rated range (miles)	Type I 120 Volt	Type II 240 Volt	Type III 480+ volt
Nissan Leaf BEV	100	73	16	8	80% in 1/2 hr
Chevy Volt PHEV	40	?	10	4	
Ford Focus BEV	≈100	?	18 to 20	3 to 4	??
Mitsubishi MiEV	83		22.5	6	80% in 1/2 hr
Toyota RAV4 BEV prototype*	100	?	28	12	

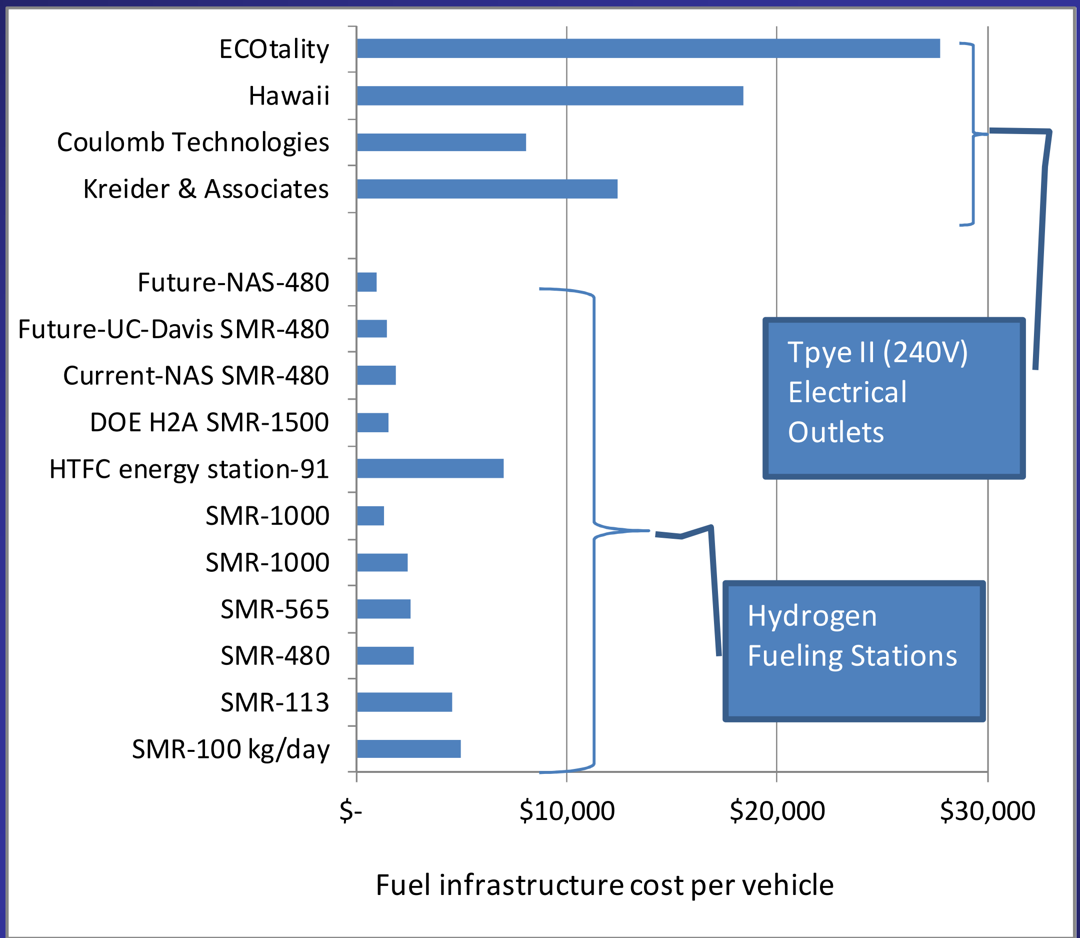
*Toyota assures reporters that the production RAV4 will have shorter charging times

BEVs outlet cost, charging times; WS - charging times- F 10 8/5 /2011

Actual Costs for initial Type II (240V) electrical outlets

	Total Cost ($M)	# of BEVs	# of outlets	Cost per BEV/PHEV
Kreider & Associates	3.72	300		$ 12,400
Coulomb Technologies	37	4600	4,600	$ 8,043
Hawaii	4.6	250	250	$ 18,400
ECOtality	230	8300	14,000	$ 27,711
Totals	275.32	13450	18,850	$ 20,470

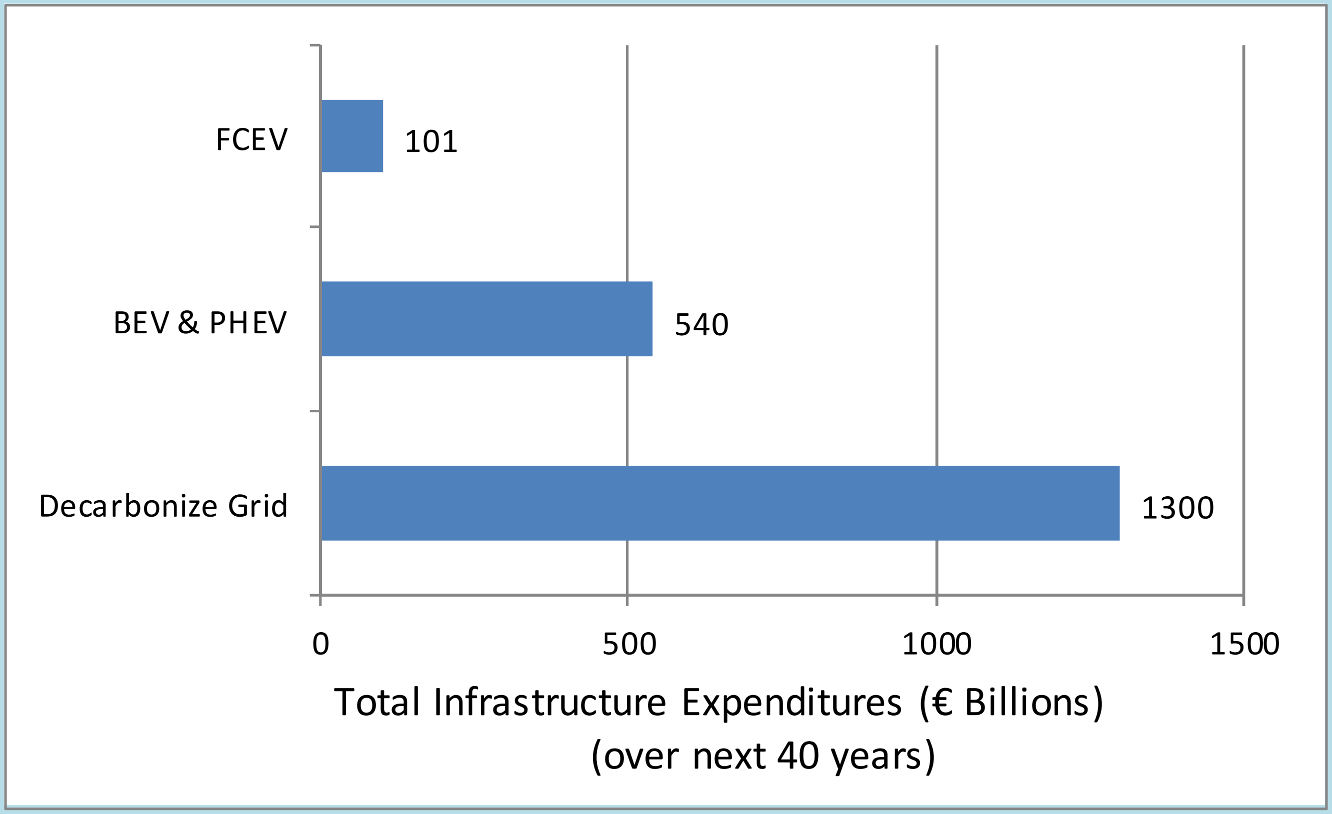
Fuel infrastructure cost per vehicle



BEVs outlet cost, charging times.XLS; WS 'H2 Cost per car' I53 10/12 /2011

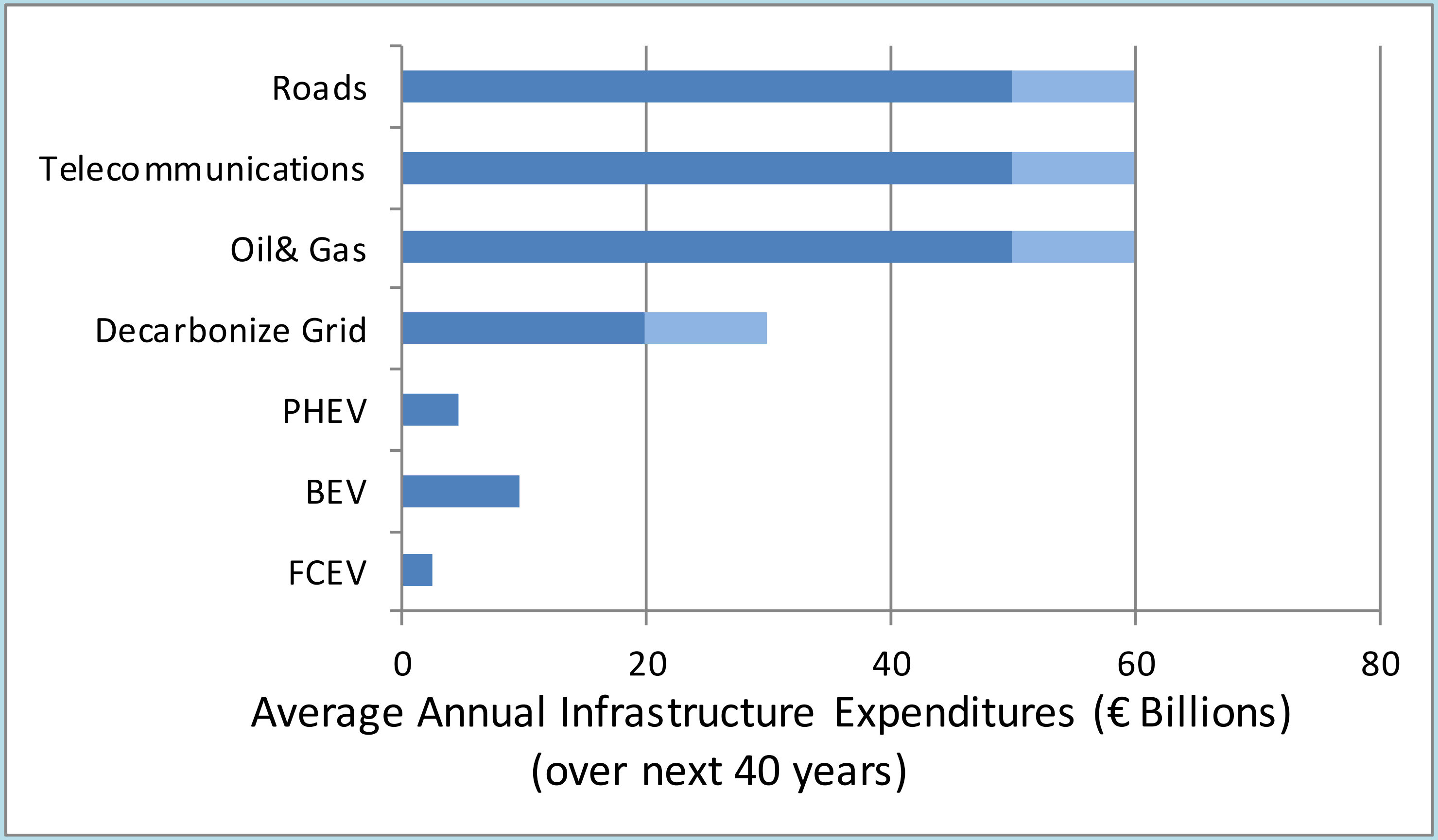
Type II Electrical outlets cost between 5.2 to 14 times more than hydrogen stations per vehicle

Total Cumulative Infrastructure Costs over 40 years **(McKinsey)**



McKinsey EU Data.xls; Tab 'Detaila'; X51 2/3/2011

Average Annual EU Infrastructure Costs over next 40 years (McKinsey)



McKinsey EU Data.xls; Tab 'Detaila'; X34 2/3/2011

BEV Market Penetration

Why not longer range BEVs?

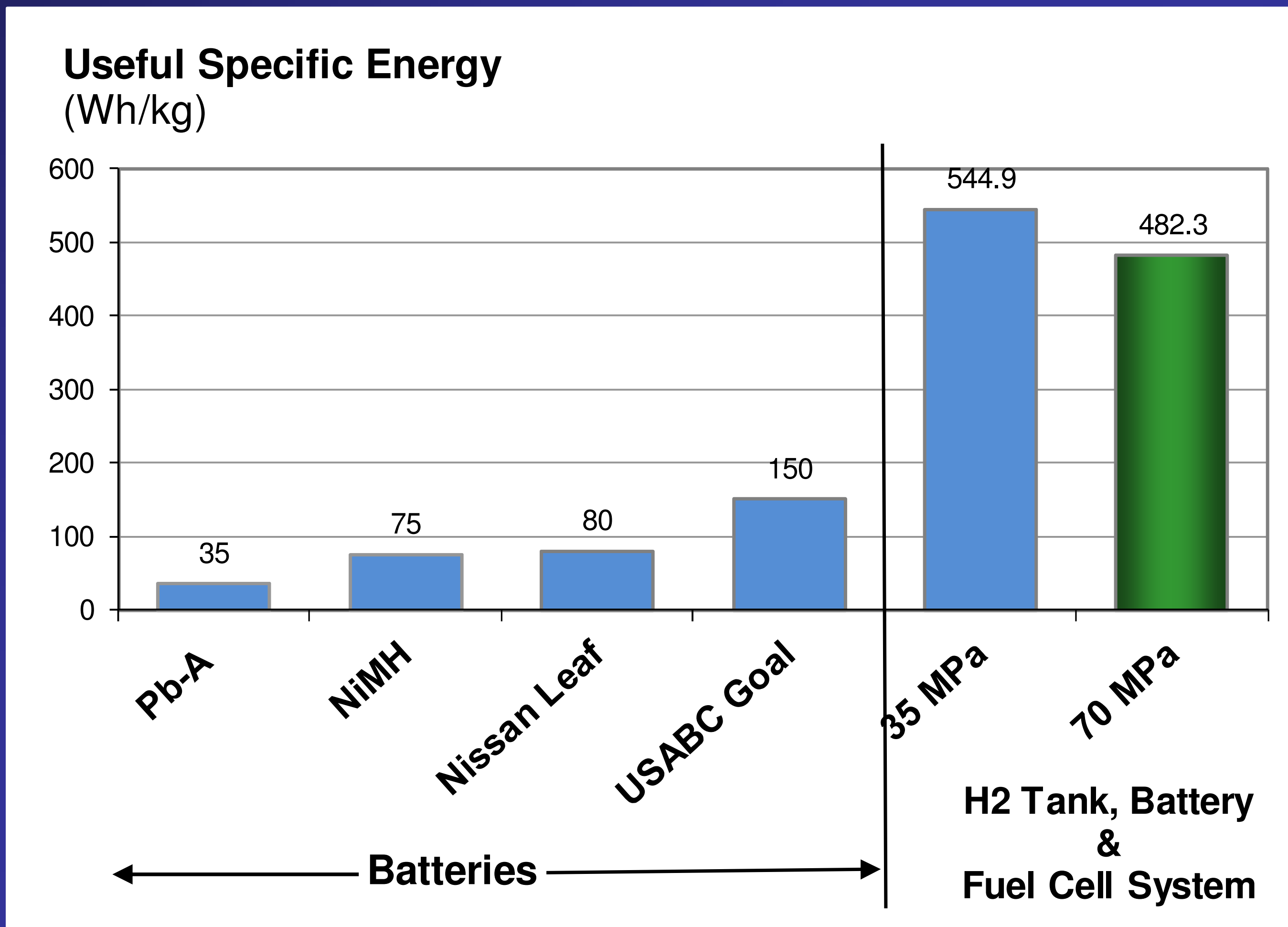
- Low Battery Specific Energy (kWh/kg)
- Low Battery Energy Density (kWh/liter)
- *MASS COMPOUNDING*

Nissan Leaf Battery Parameters compared to USABC long-term commercialization goals

	Specific Energy	Specific Power	Power Density	Energy Density
	Wh/kg	kW/kg	kW/L	kWh/L
Nissan Leaf Battery	80	0.3	0.3	0.0261
USABC long-term commercialization goals	150	0.46	0.46	0.230

Nissan Leaf Battery: 24 kWh useable energy; 300 kg mass, 90 kW power & 918 liters volume (estimated from two orthogonal photos)

Useful Specific Energy



Wt_Vol_Cost.XLS; Tab 'Battery'; S61 - 10/25/2011

Mass Compounding

- Adding batteries to increase range requires:
  - Slightly larger mechanical structure
  - Slightly larger suspension systems
  - Slightly larger brakes
- Which requires still more batteries to provide range and acceleration required

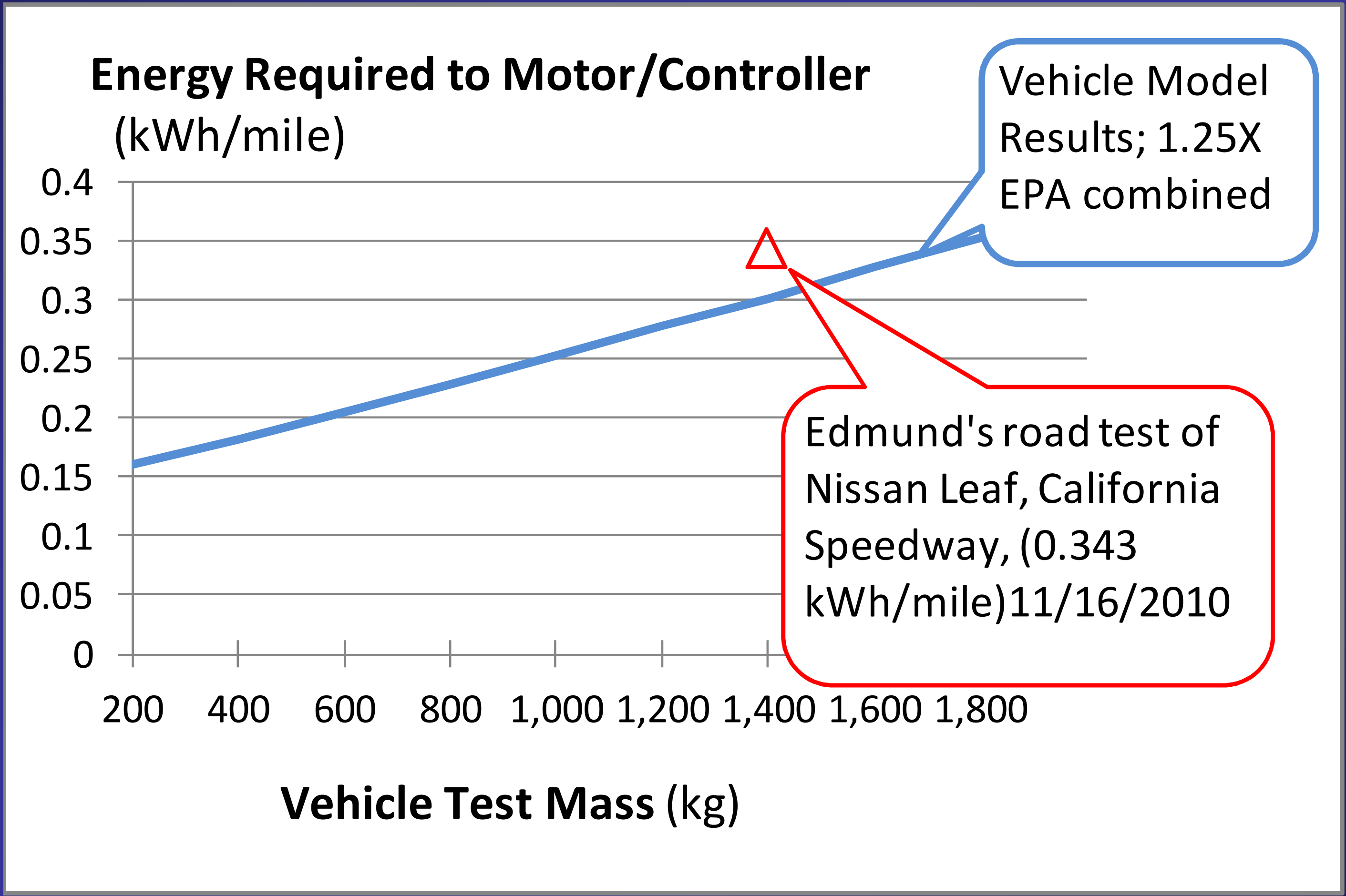
Mass Compounding of Late Model US cars

- Malen & Reddy (U. of Michigan) determined that adding 100 kg of batteries to a vehicle requires 59.8 kg of added mass to non-powertrain vehicle subsystems*.

- The **EV motor mass** increases with increased vehicle mass
- **Battery mass** increases with increased vehicle mass to maintain safe acceleration and to achieve the desired range

- *D. E. Malen & K. Reddy, "Preliminary vehicle mass estimation using empirical subsystem influence coefficients," University of Michigan, May 9, 2007 (revised June 26, 2007), available at: http://www.a-sp.org/database/custom/Mass%20Compounding%20-%20Final%20Report.pdf

Energy per mile required from battery or FC



work/vehicles/battery/Vehicle.XLS; Tab 'FUDS'; V662 - 10 / 9 / 2011

BEV test mass estimation with and without mass compounding

		Est Range	Battery capacity:		
	kWh/mile	Miles	24	kWh	
Model	0.337	71.2		2 people	1681 kg
Edmund's road test	0.343	70.0		2 people	1681 kg
Model	0.367	65.4		5 people	1921 kg
			Leaf curb mass: 1521 kg		

work/vehicles/battery/Vehicle.XLS; Tab 'FUDS'; AC 654 - 10 / 11 / 2011

Without mass compounding: to increase range from 65 miles to 100 miles requires the addition of 35miles x .367 kWh/mile = 12.8 kWh / .08 kWh/kg = 161 kg of extra battery for a total test mass of 1921 +161= **2,082 kg**

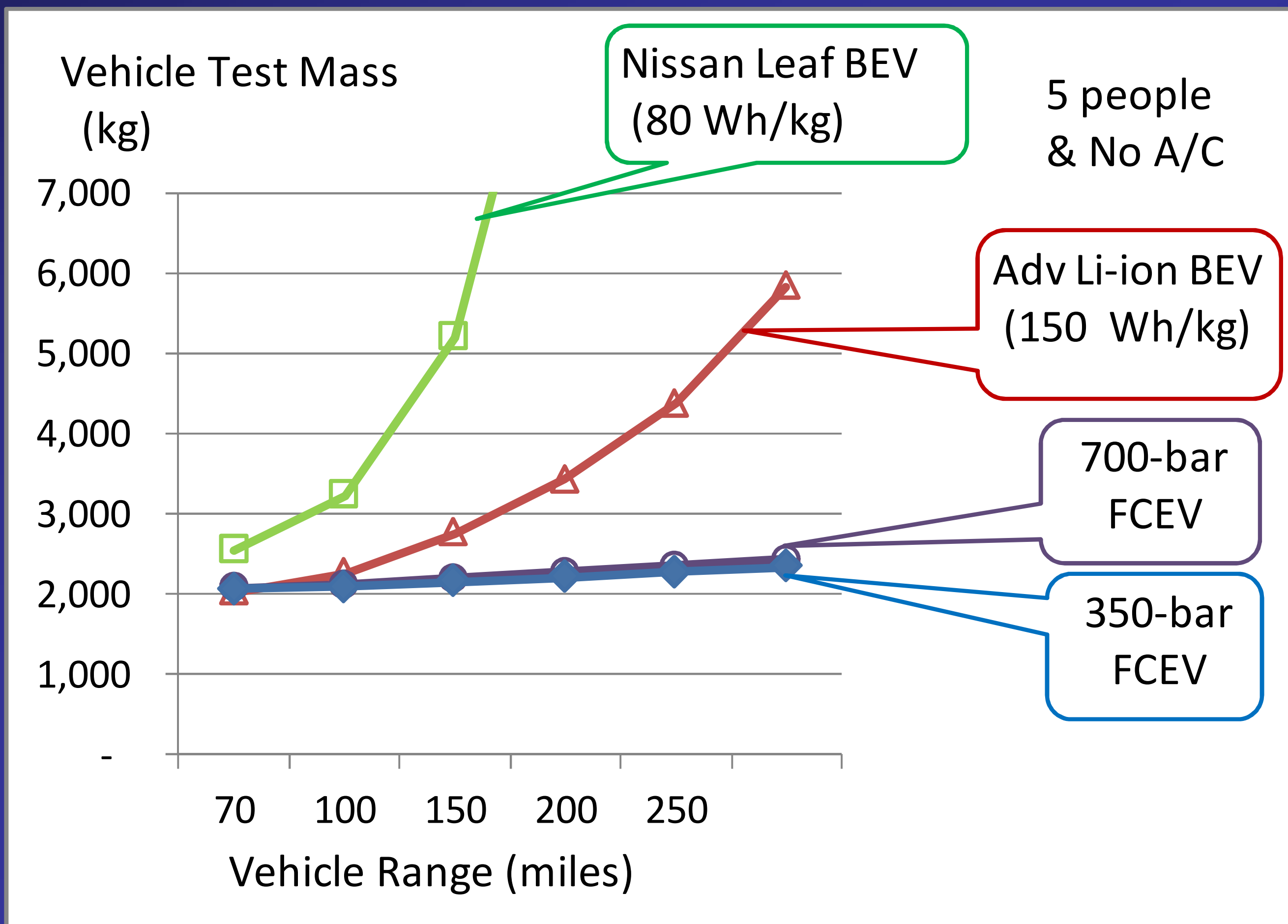
With mass compounding, the final BEV test mass for 100 miles range is **3,236 kg**, a 55% increase over the simple linear calculation!

Deloitte survey" Unplugged: electric vehicle realities versus consumer expectations*"

- **63% of potential EV buyers expect greater than 300 miles range** on one charge
- 23% expect charging in less than 30 minutes

*Deloitte Survey "Unplugged: Electric vehicle realities versus consumer expectations"
Published October 05, 2011, http://www.foxnews.com/leisure/2011/10/05/survey-says-electric-cars-dont-meet-expectations-customers/

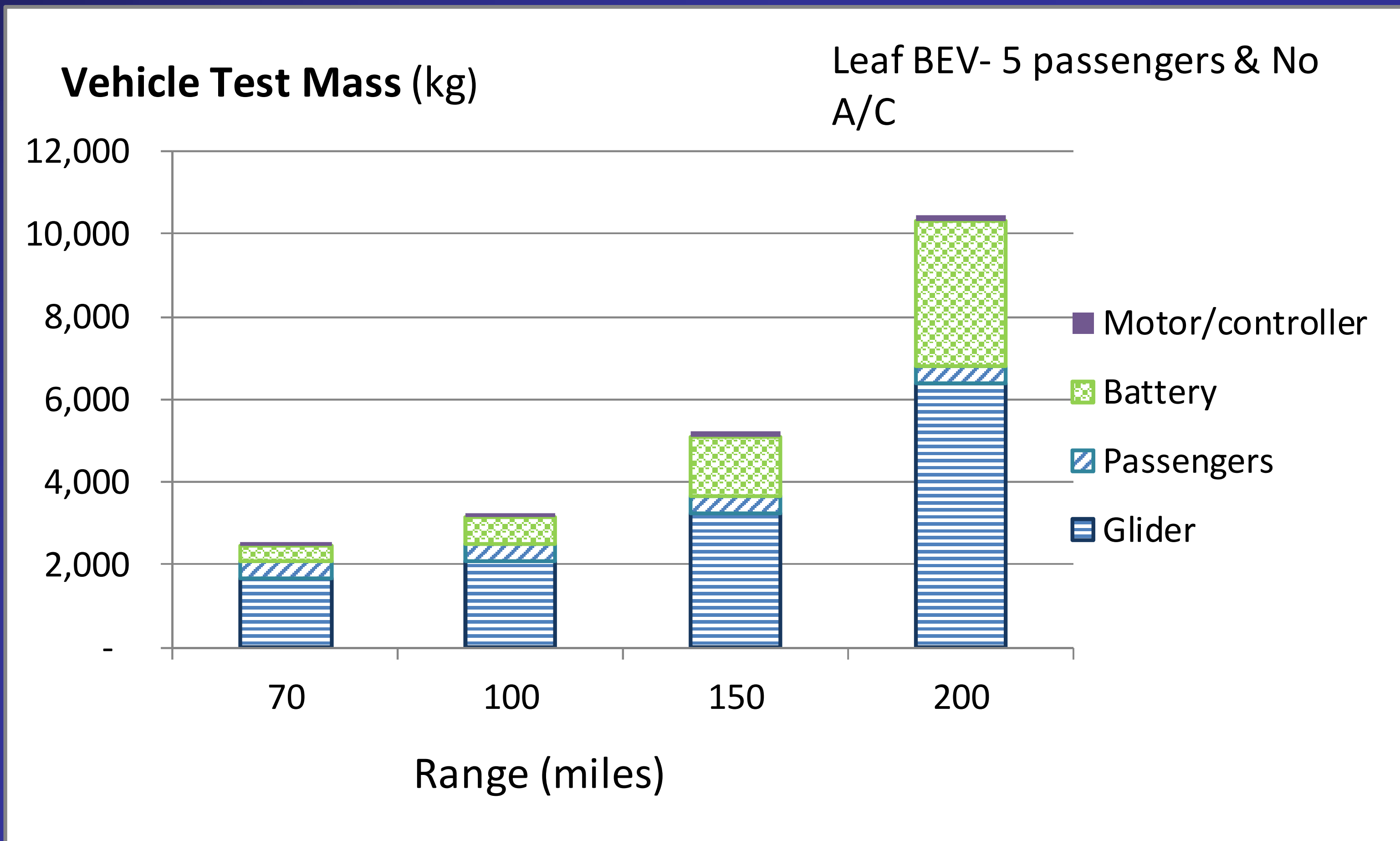
Vehicle Test Mass with Mass Compounding for BEVs & FCEVs



BPEV mass,vol,cost vs range charts RevB.XLS; Tab 'Equation-Leaf'; BR58 - 10/9/2011

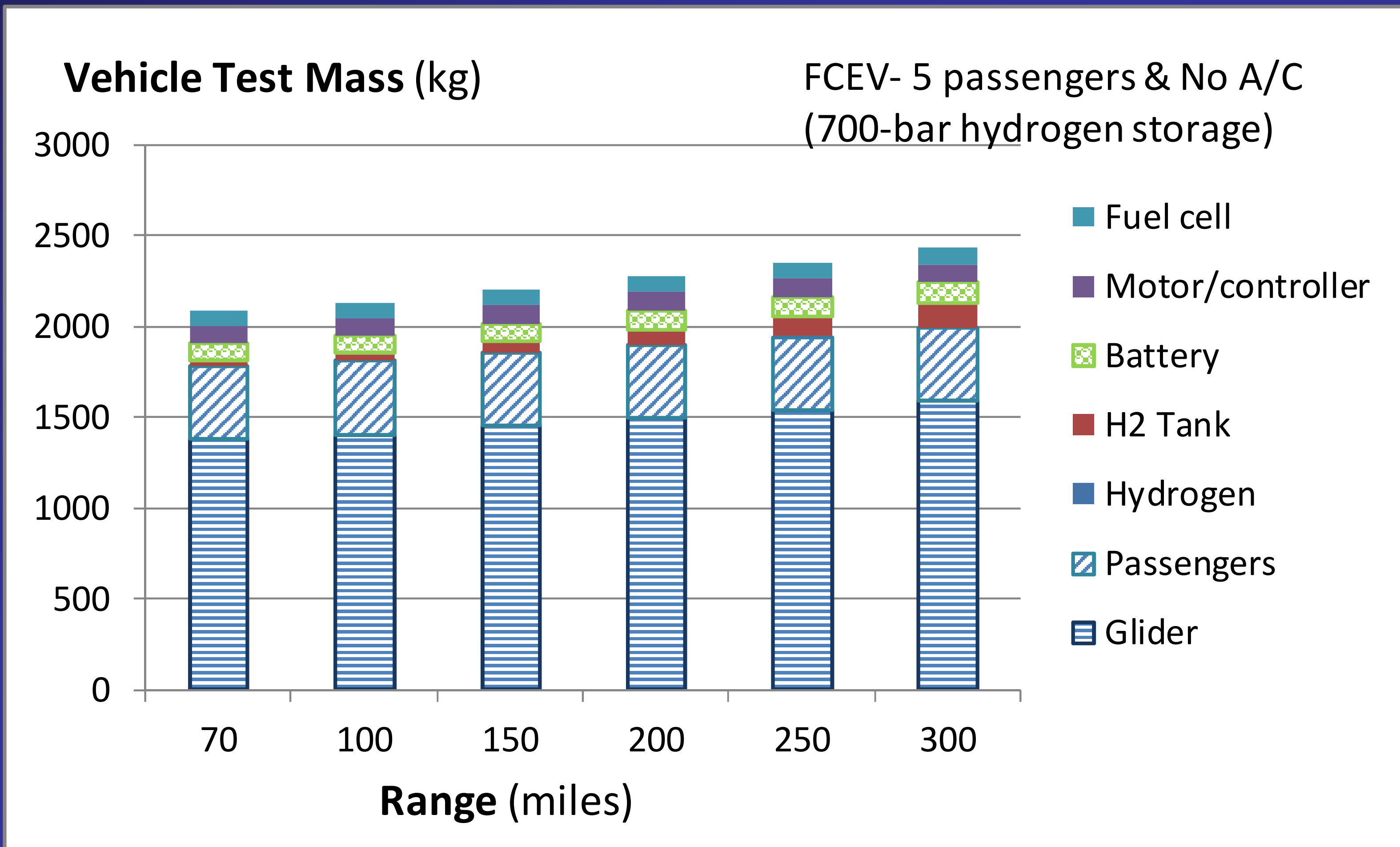
"Adv Li-ion battery" assumes that the USABC long-term commercialization goals are achieved (150 Wh/kg; 230 Wh/Liter).

BEV Mass Compounding Elements



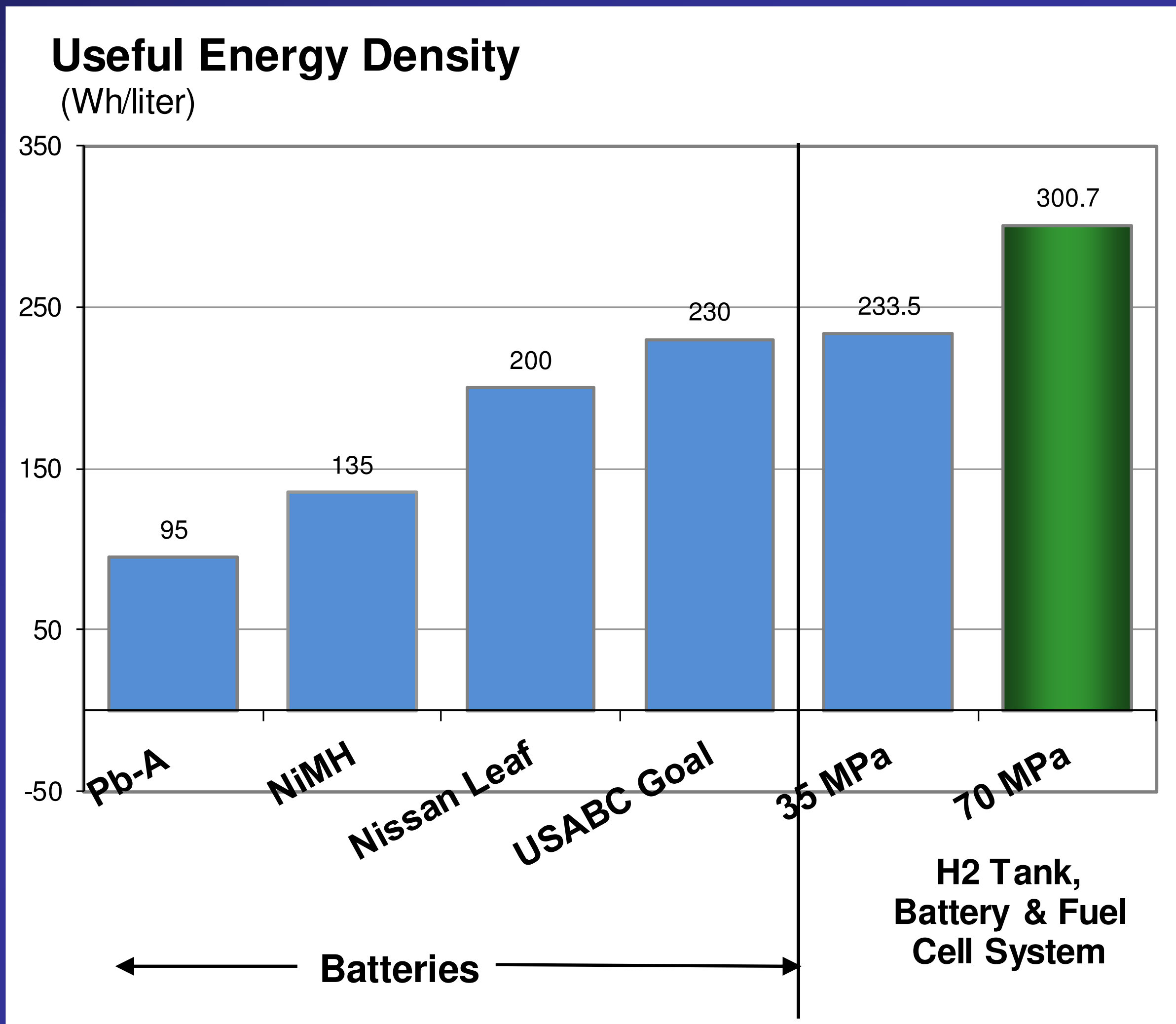
BPEV mass,vol,cost vs range charts RevB.XLS; Tab 'Equation-Leaf'; Q-163 - 10 / 10 / 2011

FCEV Mass Compounding Elements



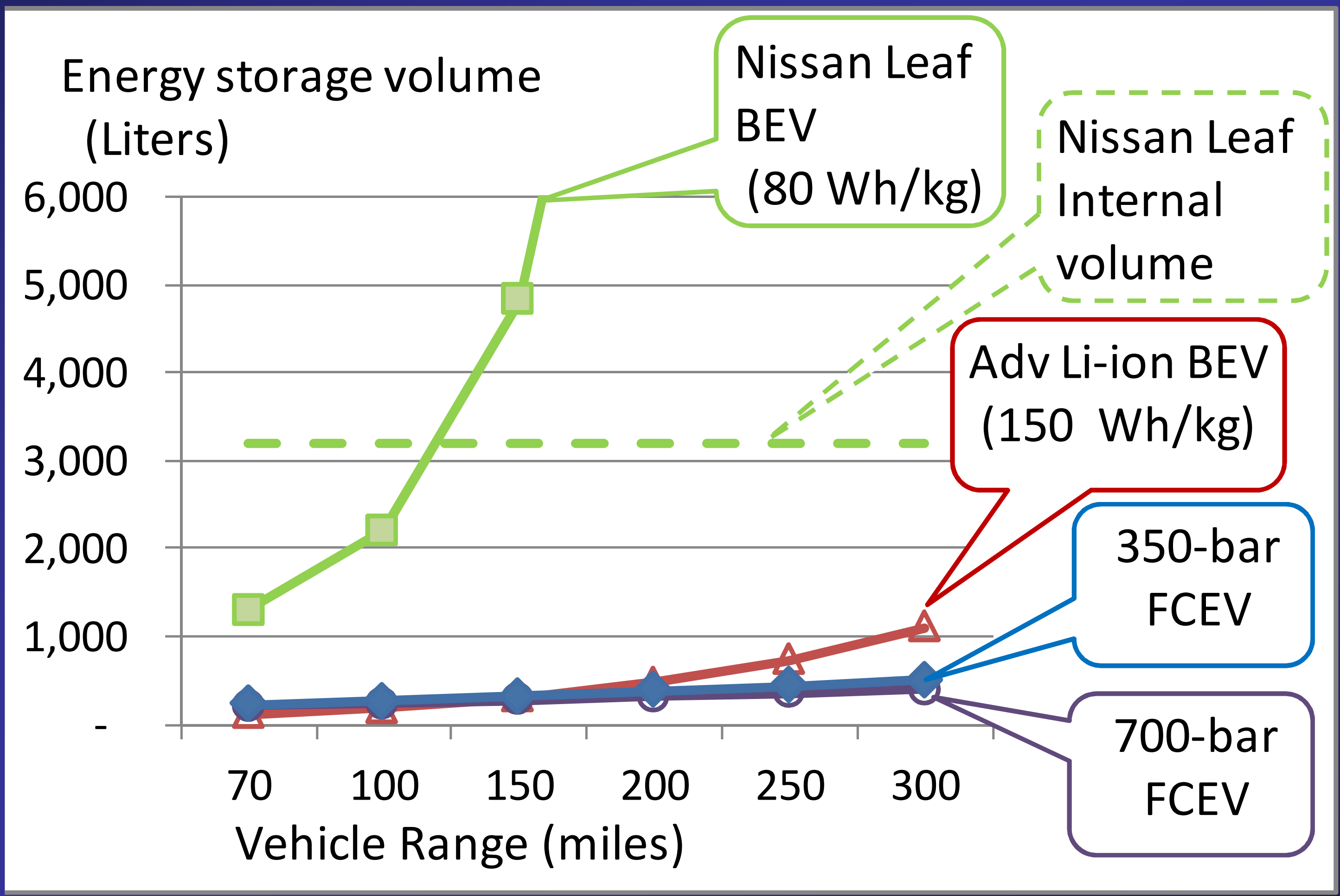
BPEV mass,vol,cost vs range charts RevB.XLS; Tab 'Equation-Leaf'; I163 - 10 / 11 / 2011

Useful Energy Density



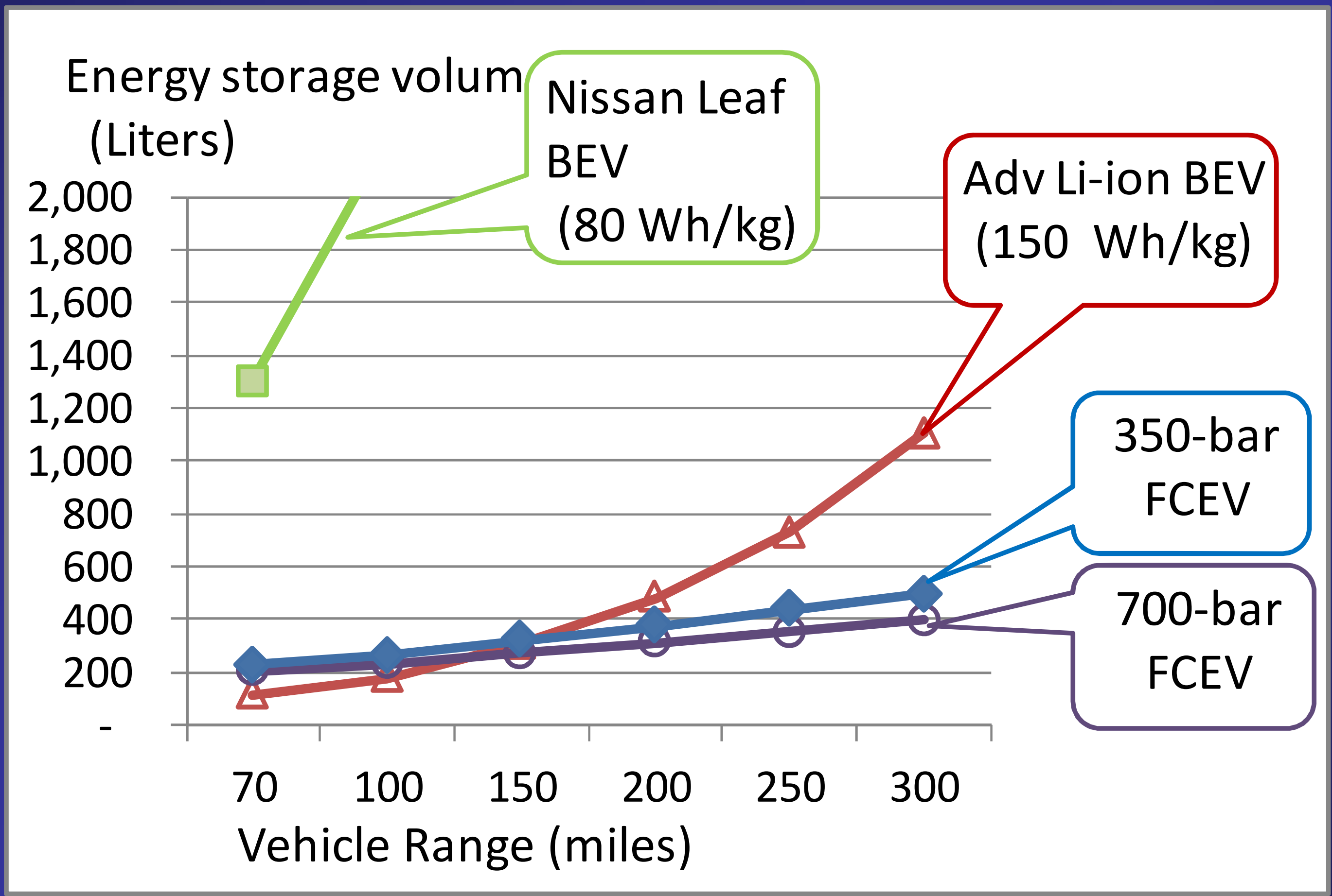
Battery & H2 Tank Wt_Vol_Cost.XLS; Tab 'Battery'; S37 - 10 / 25 / 2011

Energy Storage Volumes for Nissan Leaf size BEVs and FCEVs



BPEV mass,vol,cost vs range charts RevB.XLS; Tab 'Equation-Leaf'; BR41 - 10 / 9 / 2011

Energy storage volume (expanded scale)



BPEV mass,vol,cost vs range charts RevB.XLS; Tab 'Equation-Leaf'; BX41 - 10/9/2011

Advanced Li-Ion assumes USABC Long-Term Commercialization Goals are Achieved

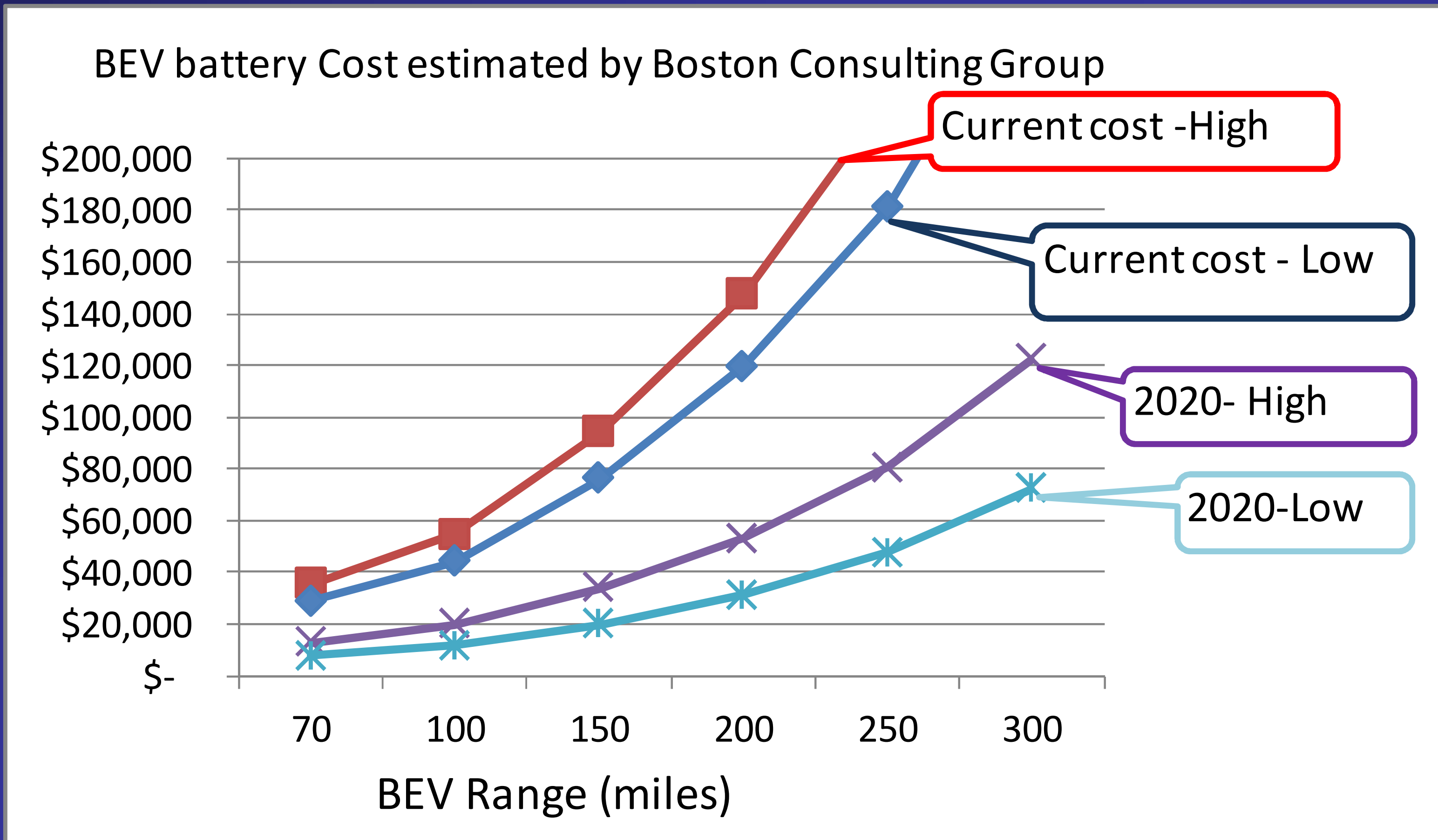
Boston Consulting Group* Battery Cost Estimates

	Battery cost ($/kWh)	
	Low	High
Current Cost	$990	$1,220
2020 costs	260	440

work/vehicles/battery/BPEV mass,vol,cost vs range charts RevB.XLS; Tab 'Equation-Leaf'; AD 104 - 10 / 25 / 2011

* A. Dinger et al, "Batteries for Electric vehicles: challenges, opportunities and the Outlook to 2020, The Boston Consulting Group (no date). Available at: http://www.bcg.com/documents/file36615.pdf

BEV Battery Pack OEM cost estimates vs. range

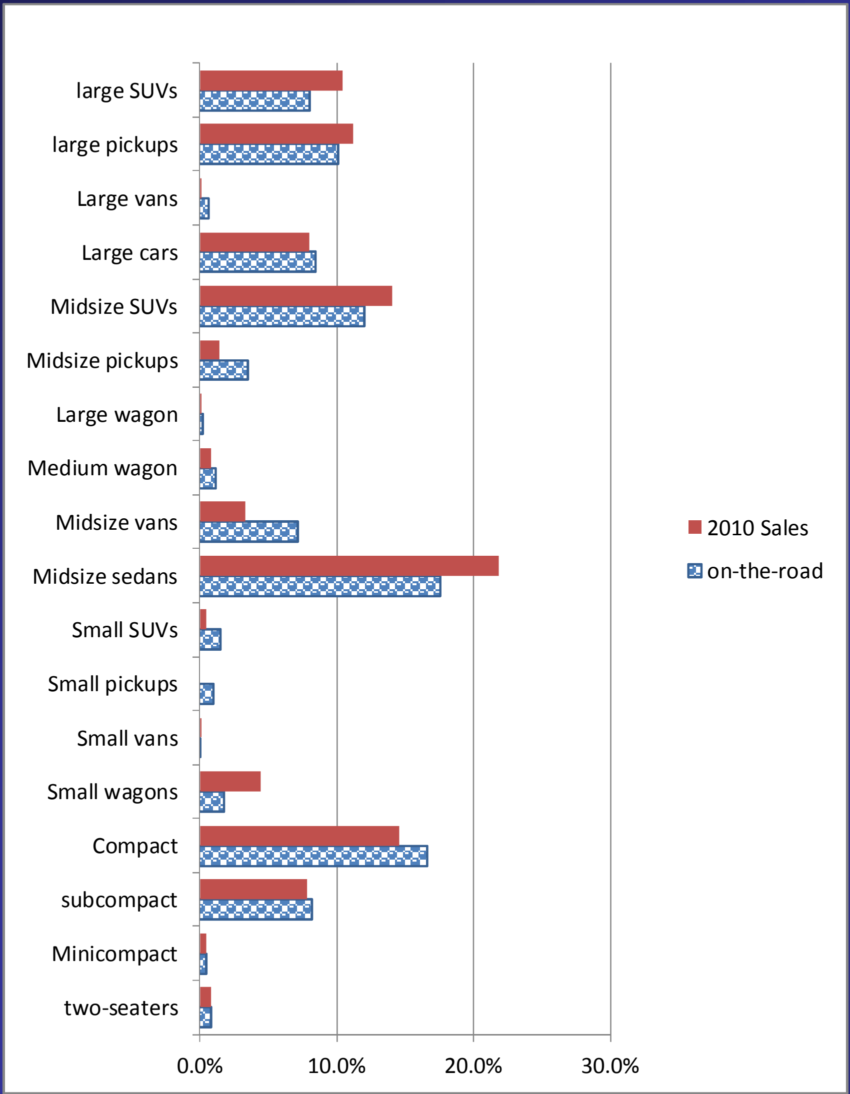


work/vehicles/battery/BPEV mass,vol,cost vs range charts RevB.XLS; Tab 'Equation-Leaf'; AL 103 - 10 / 25 / 2011

Market Potential for BEVs

- Assuming that BEVs can only be sold for small vehicles, how many small vehicles are in the current US car fleet?
- And what % of GHGs and oil consumption do these small cars represent?
- (McKinsey & Company estimated that 50% of all vehicles in the EU that generate 75% of all GHGs are too big or travel too far to be affordably powered by batteries.

Distribution of US Car sizes



EPA f.e. vs. veh class OTR by class.XLS; Tab 'Sales by class'; Y206 - 10 / 10 / 2011

	% on the road	% of 2010 Sales
two-seaters	0.9%	0.8%
Minicompact	0.5%	0.4%
subcompact	8.2%	7.8%
Compact	16.7%	14.6%
Small wagons	1.8%	4.5%
All Small cars	28.1%	28.1%
Small vans	0.1%	0.1%
Small pickups	1.1%	0.0%
Small SUVs	1.6%	0.5%
All Small Vehicles	30.9%	28.7%
Midsize sedans	17.6%	21.9%
Midsize vans	7.2%	3.3%
Medium wagon	1.2%	0.8%
Large wagon	0.2%	0.1%
Midsize pickups	3.6%	1.4%
Midsize SUVs	12.0%	14.0%
Large cars	8.5%	8.0%
Large vans	0.7%	0.1%
large pickups	10.2%	11.2%
large SUVs	8.0%	10.4%

EPA f.e. vs. veh class OTR by class.XLS; Tab 'Sales by class'; E186 - 10 / 10 / 2011

Previous Assumption for GHG reductions:

- 100% replacement of ICVs with BEVs

New Assumption

- BEVs will replace :
  - All small cars,
  - All small pickup trucks
  - All small SUVs
  - All small vans
  - And 50% of all midsize sedans

Table 4. Current BEVs available or under development

			EPA range		Charging Hours	
		Type	(km)	(miles)	120-V	240-V
Nissan	Leaf	5-passenger	117.5	73	21	8
Ford	Transit Connect	Small van	128.7	80	27	8
Toyota	RAV4	Small SUV	129-193	80-120	28*	12*
Smart	Fortwo	2-seater	113-161	70-100		3.5**
Wheego	Life	2-seater	160.9	100		5***
Mitsubishi	i-MiEV	4-passenger	99.8	62	14	7
Think	City	4-passenger	160.9	100	18	8 to 10

*RAV4 charging times for prototype; production unit charging time expected to be shorter

**Smart Fortwo charging from 20% to80% SOC; 8 hours for full charge

***Wheego charging time for 50% to 100% SOC

AEO 2011 US Grid Mix Projections through 2035 assuming no carbon constraints

No Carbon constraints	2010	2015	2020	2025	2030	2035
Coal	44.8%	42.3%	43.5%	45.5%	45.5%	45.2%
Oil	1.1%	1.0%	1.0%	1.0%	0.9%	0.9%
Natural gas	24.6%	23.8%	22.3%	20.8%	22.1%	23.4%
All fossil fuels	70.6%	67.1%	66.7%	67.2%	68.5%	69.5%
Nuclear	19.4%	19.8%	19.7%	18.6%	17.5%	16.7%
renewables	10.0%	13.1%	13.6%	14.2%	14.0%	13.8%

work/electric utilities/ AEO-2011 alternative scenarios.XLS, DD 382;10/24/2011

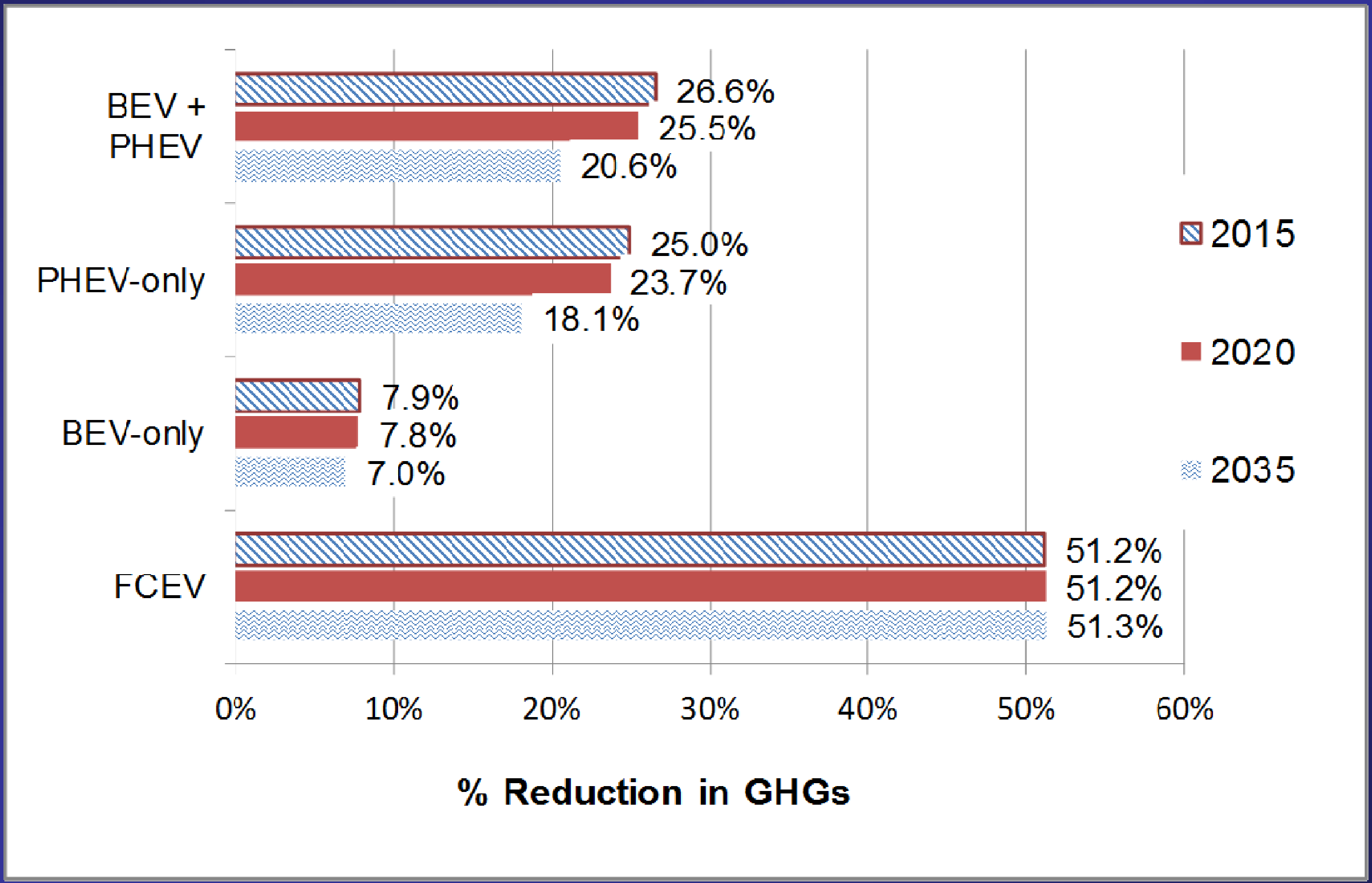
Impact of small BEVs* on US GHGs and Oil Consumption

	# of LDVs on the road	% VMT	% gasoline	% GHGs	% ICV GHG savings	% BEV grid GHGs	Net GHG Savings (2015)
Small cars & trucks suitable for BEVs:	**39.6%**	**27.2%**	**24.9%**	**25.2%**	**-25.2%**	**17.3%**	**-7.91%**
Larger cars & trucks:	**60.4%**	**72.8%**	**75.1%**	**74.8%**			

EPA f.e. vs. veh class OTR by class (rev B).XLS; Tab 'Sales by class';AN135 - 10/24/2011

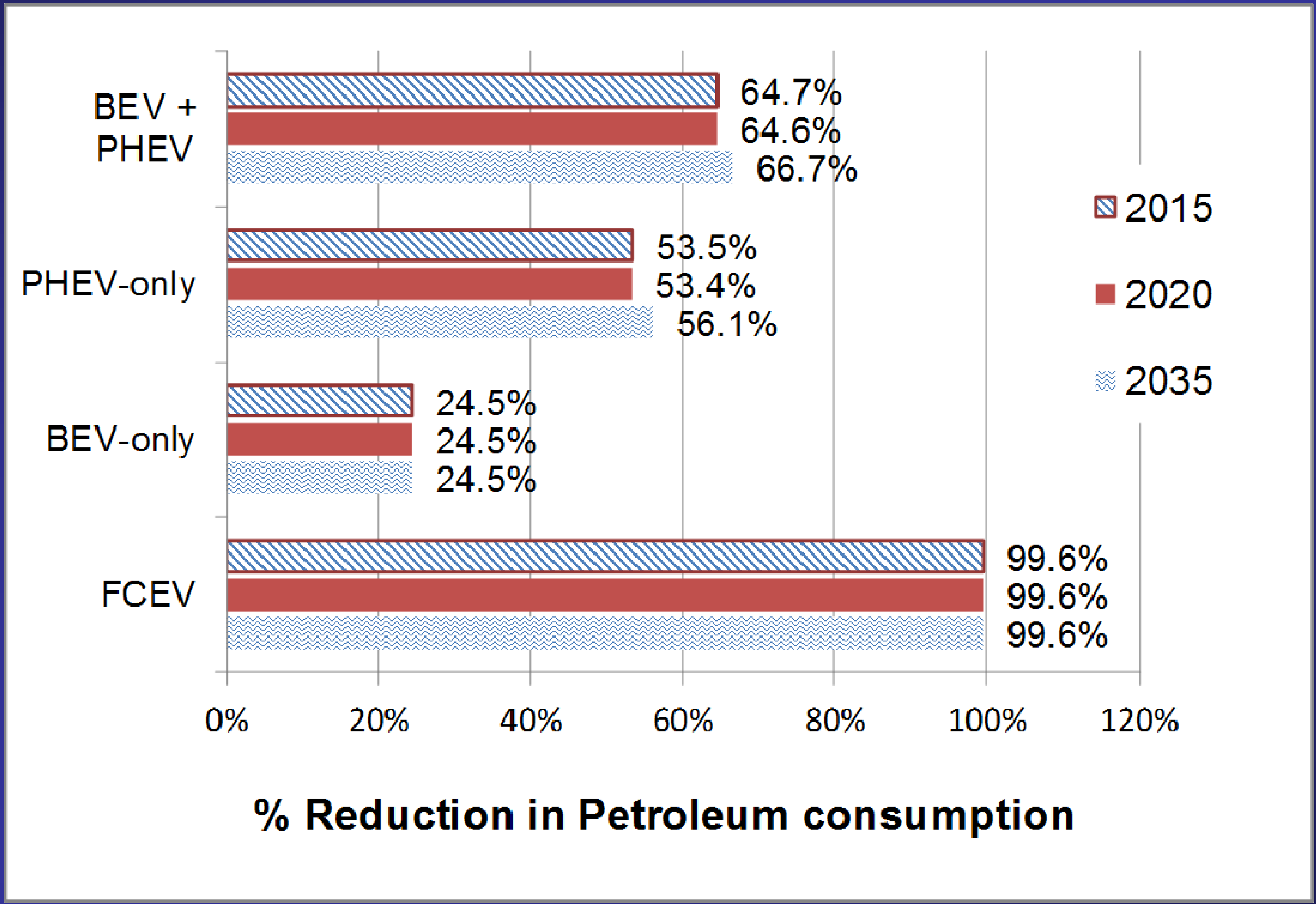
* Includes all two-seaters, all mini-compact, subcompact, all compact, all small sedans, all small wagons, all small vans, all small pickup trucks, all small SUVs & 50% of all midsize sedans.

Maximum GHG Reductions for BEVs, PHEVs through 2035



work/emmissions/Car GHG and criteria pollutants (Rev C).XLS WS 'Best Fuels' H 140 10/28/2011

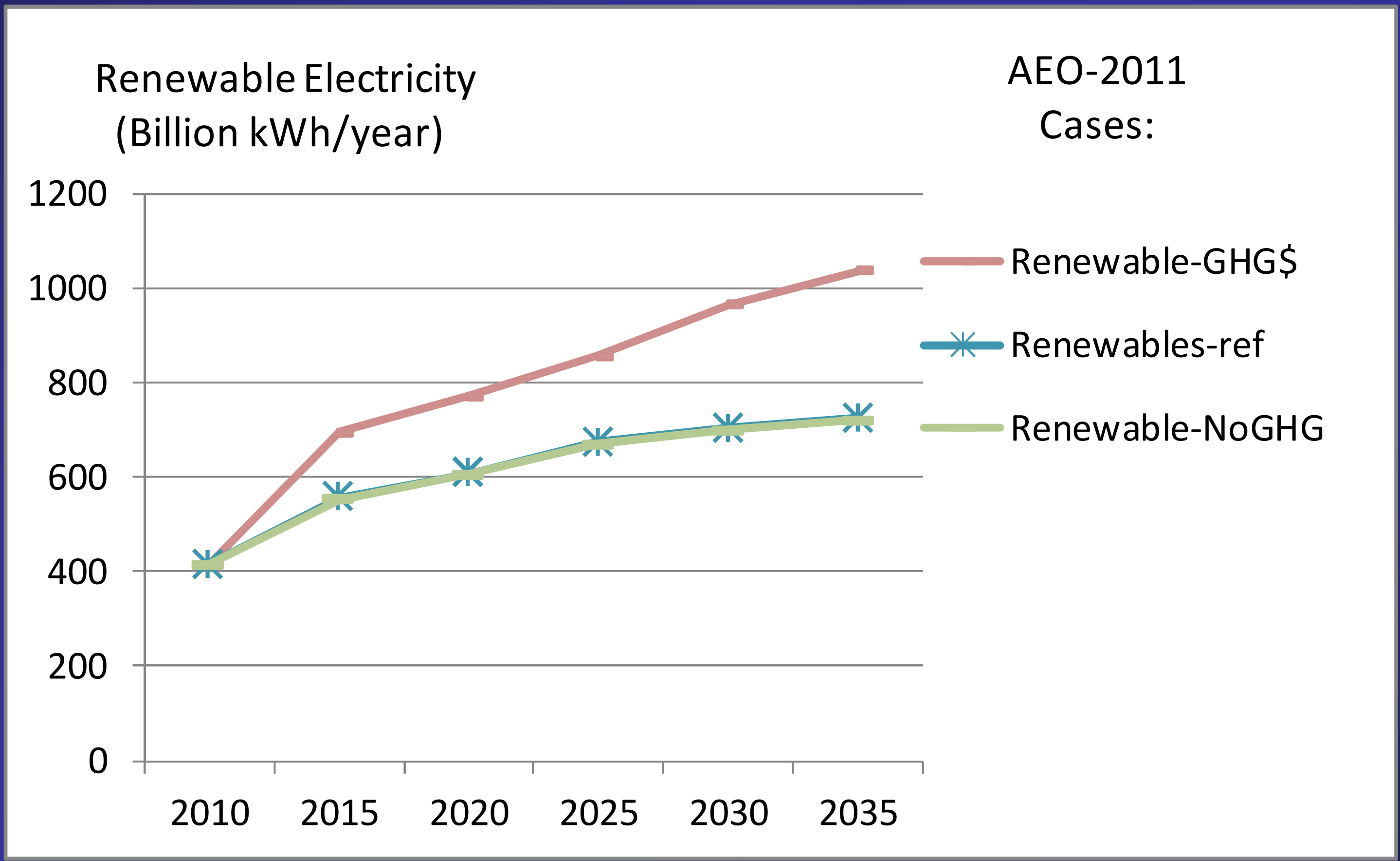
Maximum Reductions in Oil Consumption for BEVs & PHEVs Through 2035



Car GHG and criteria pollutants (Rev C).XLS: WS 'Best Fuels' R 140 10/28/2011

Greenhouse Gas Pollution over time with hydrogen and electricity "greening" over time

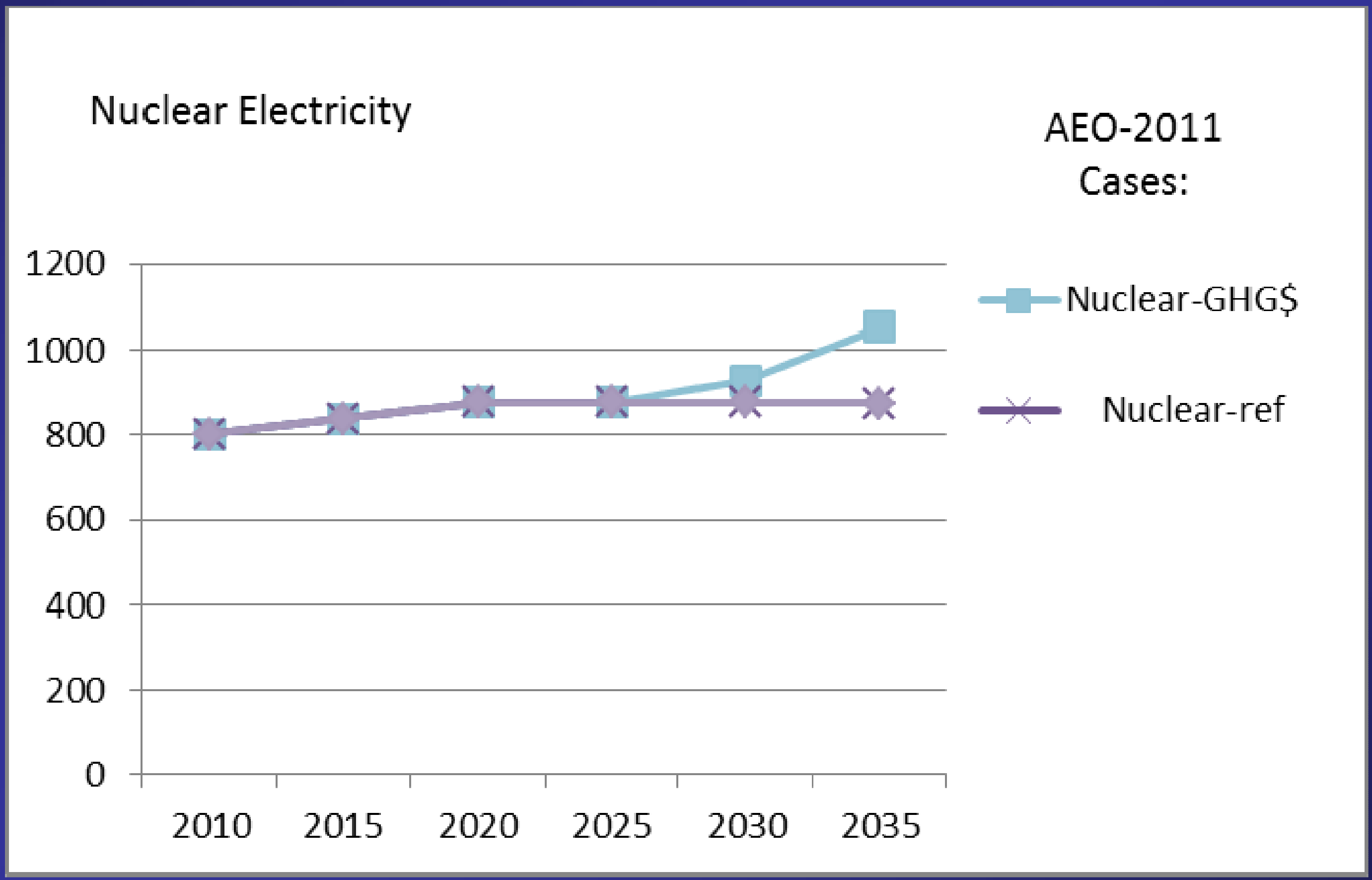
AEO-2011 Projections with carbon constraints*



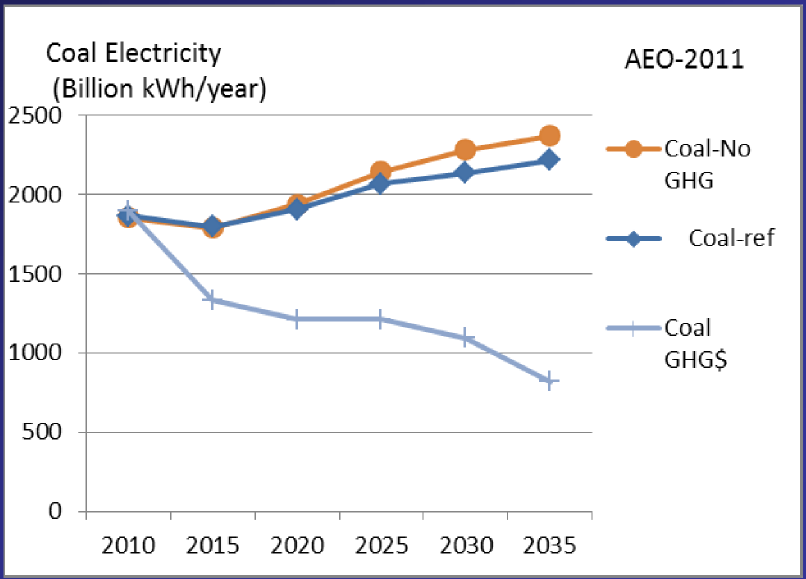
work/electric utilities/ AEO-2011 alternative scenarios.XLS, DD 391;10/24/2011

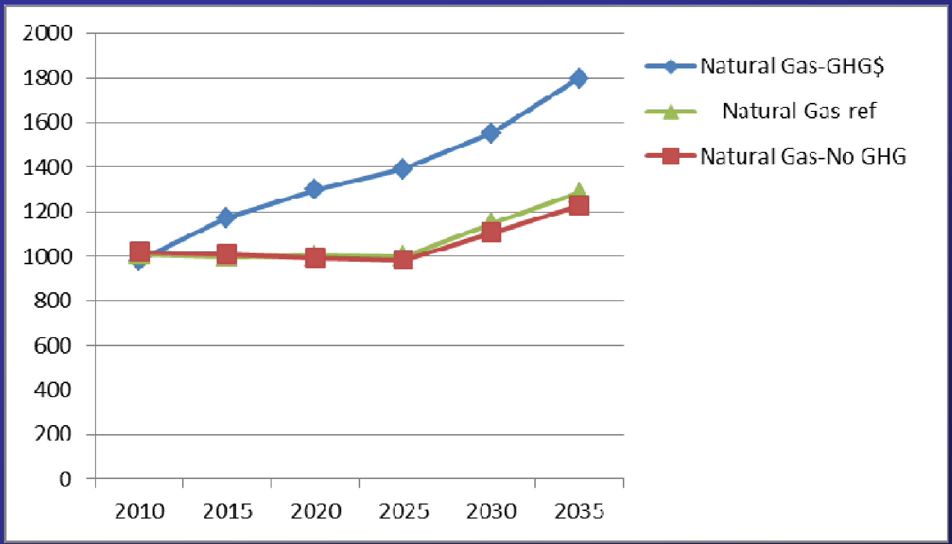
*EIA assumes a carbon fee of $25/ton in 2015, rising to $77/ton by 2035

Nuclear electricity projections with carbon constraints

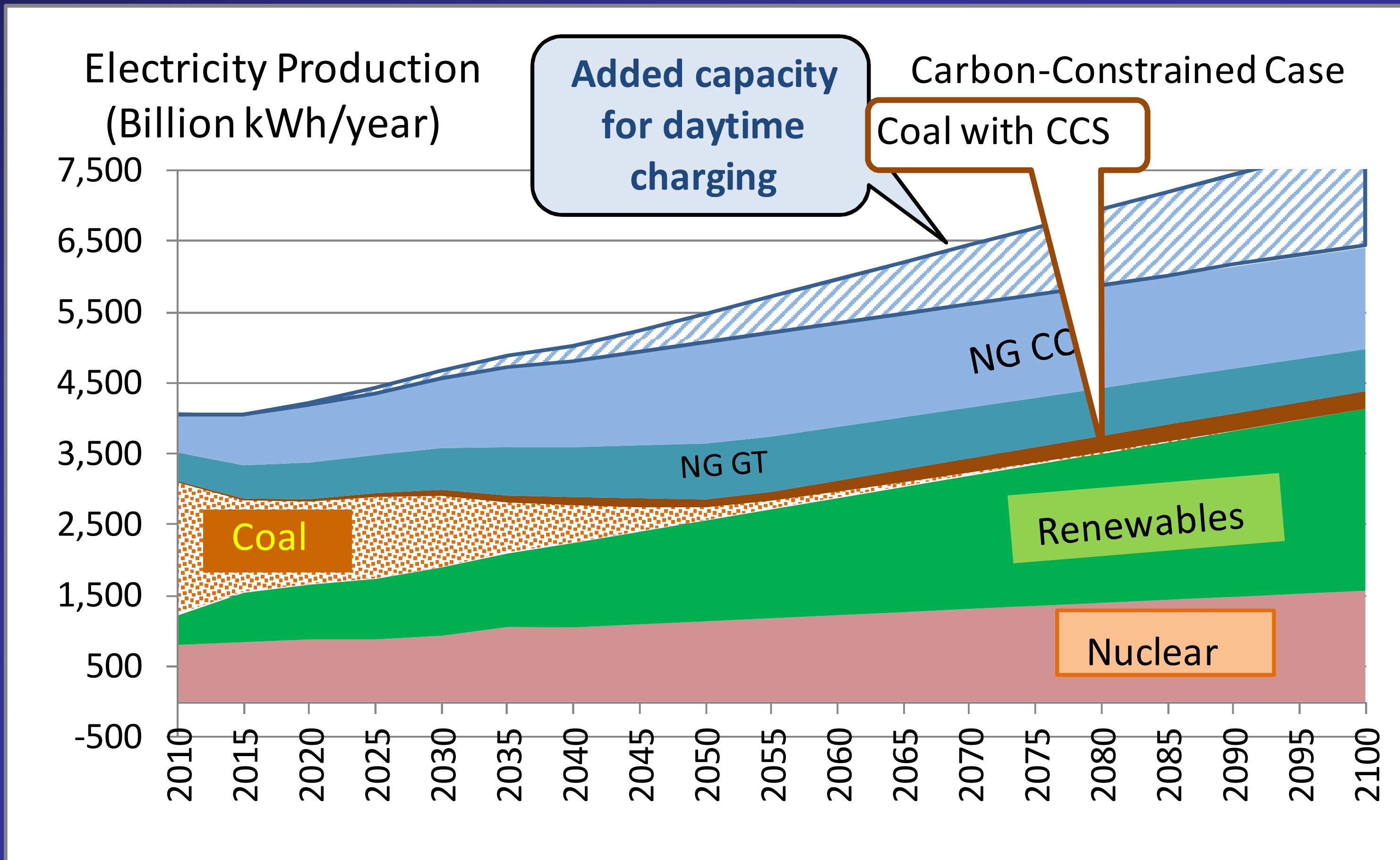


Other AEO2011 projections with carbon constraints



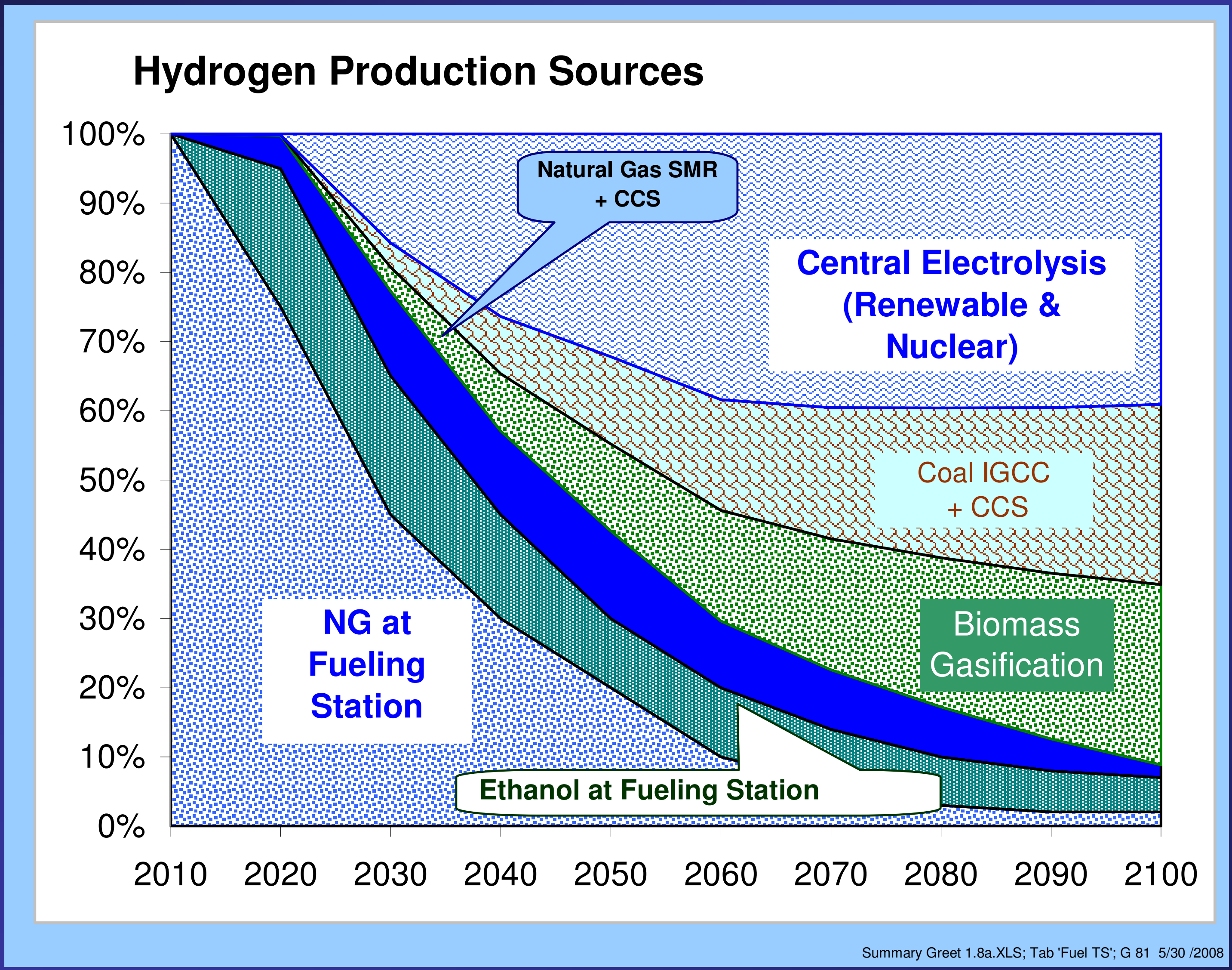


Greening of the Grid



H2Gen: GHG.XLS, Tab 'Climate Change Projections'; AG 205;10/26/2011

Greening of Hydrogen

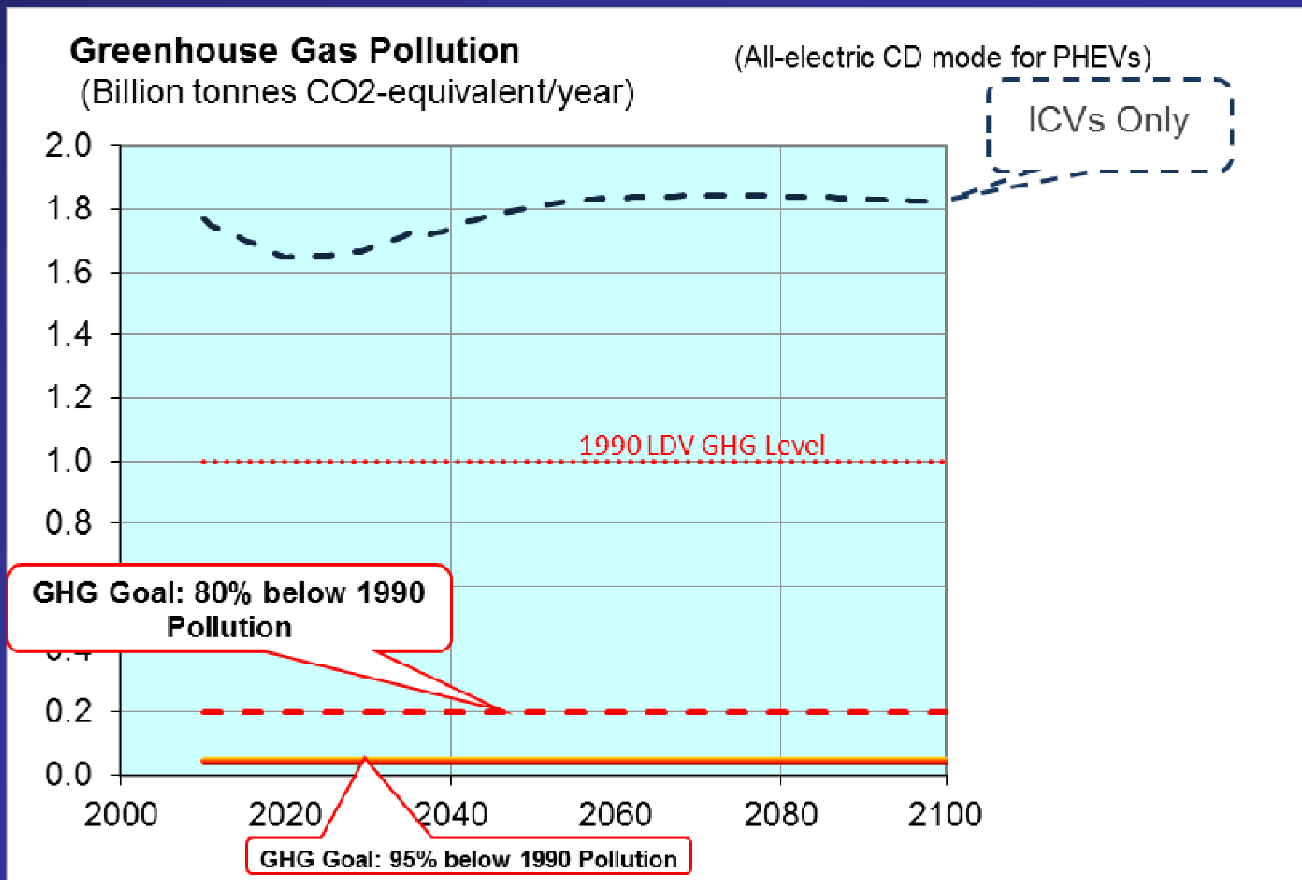


SMR = steam methane reformer (hydrogen from natural gas)

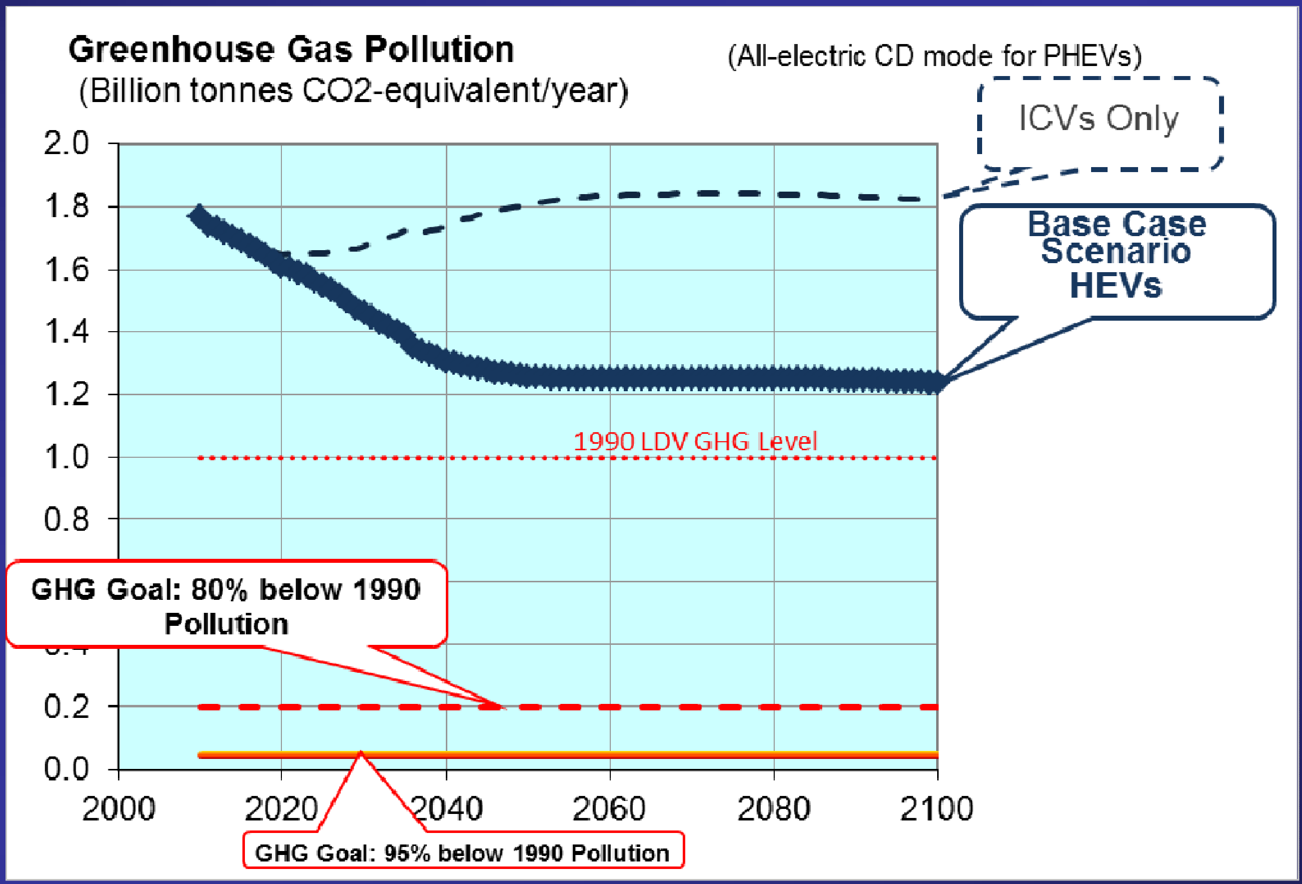
CCS = carbon capture and storage

IGCC = integrated (coal) gasification combined cycle

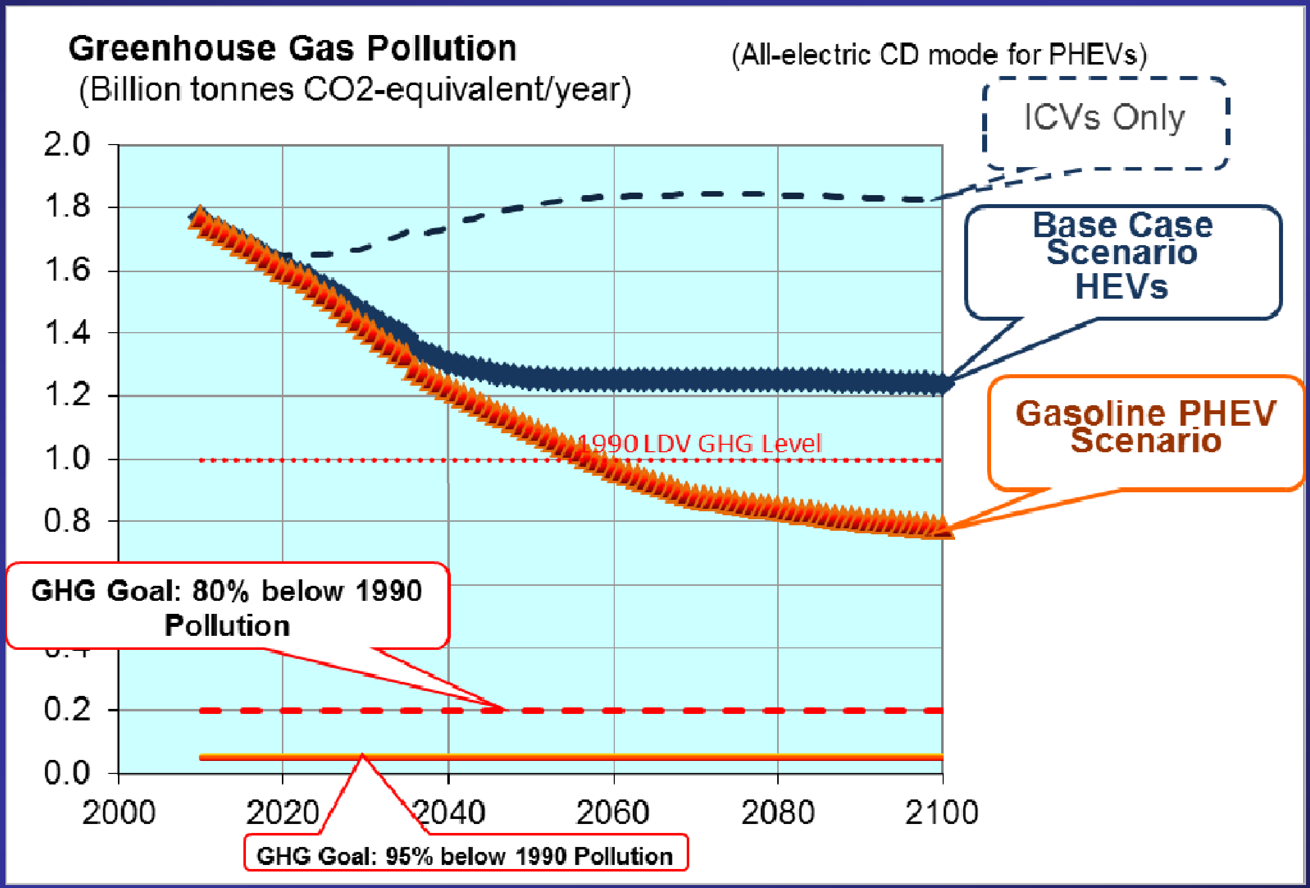
GHG with no alternative vehicles



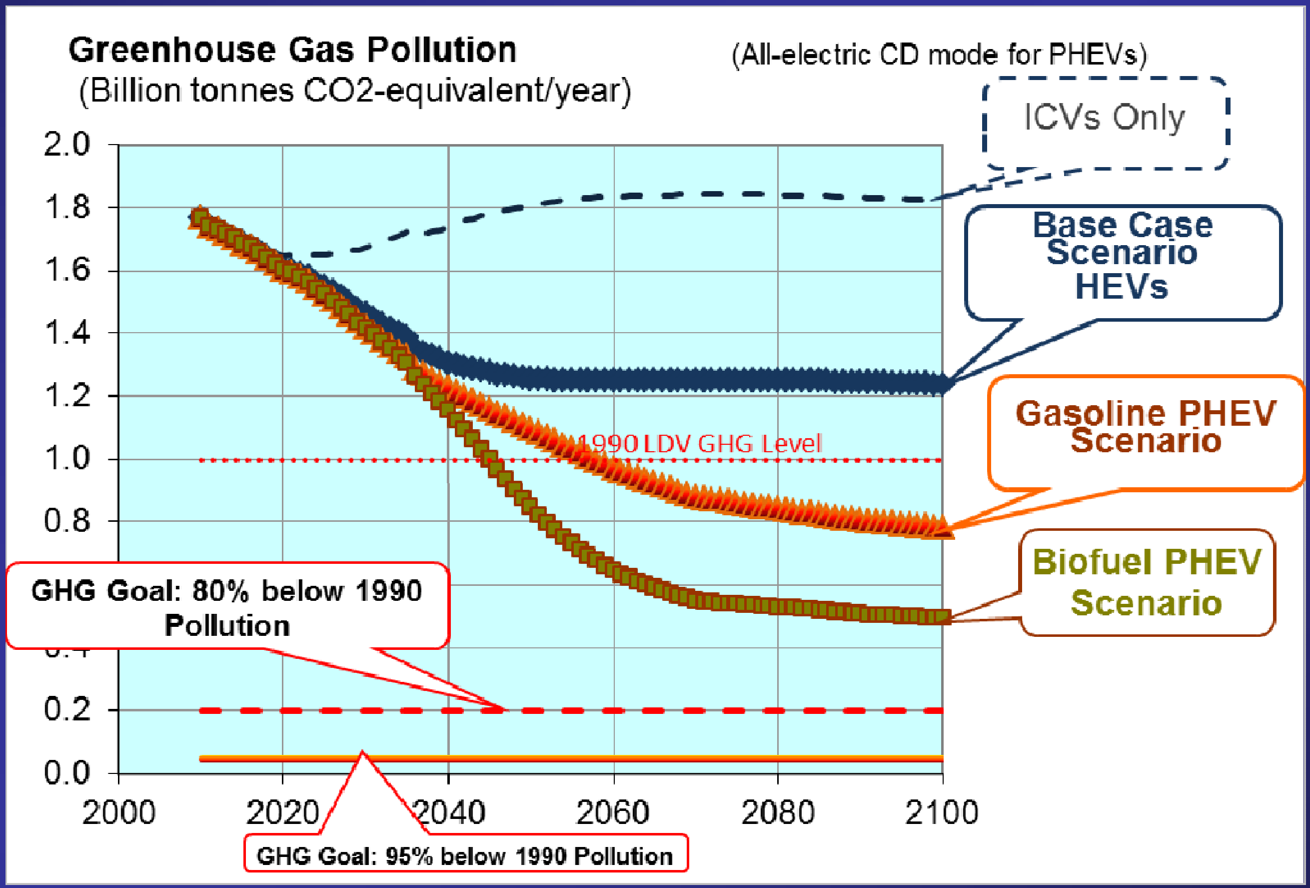
GHGs with Gasoline HEVs



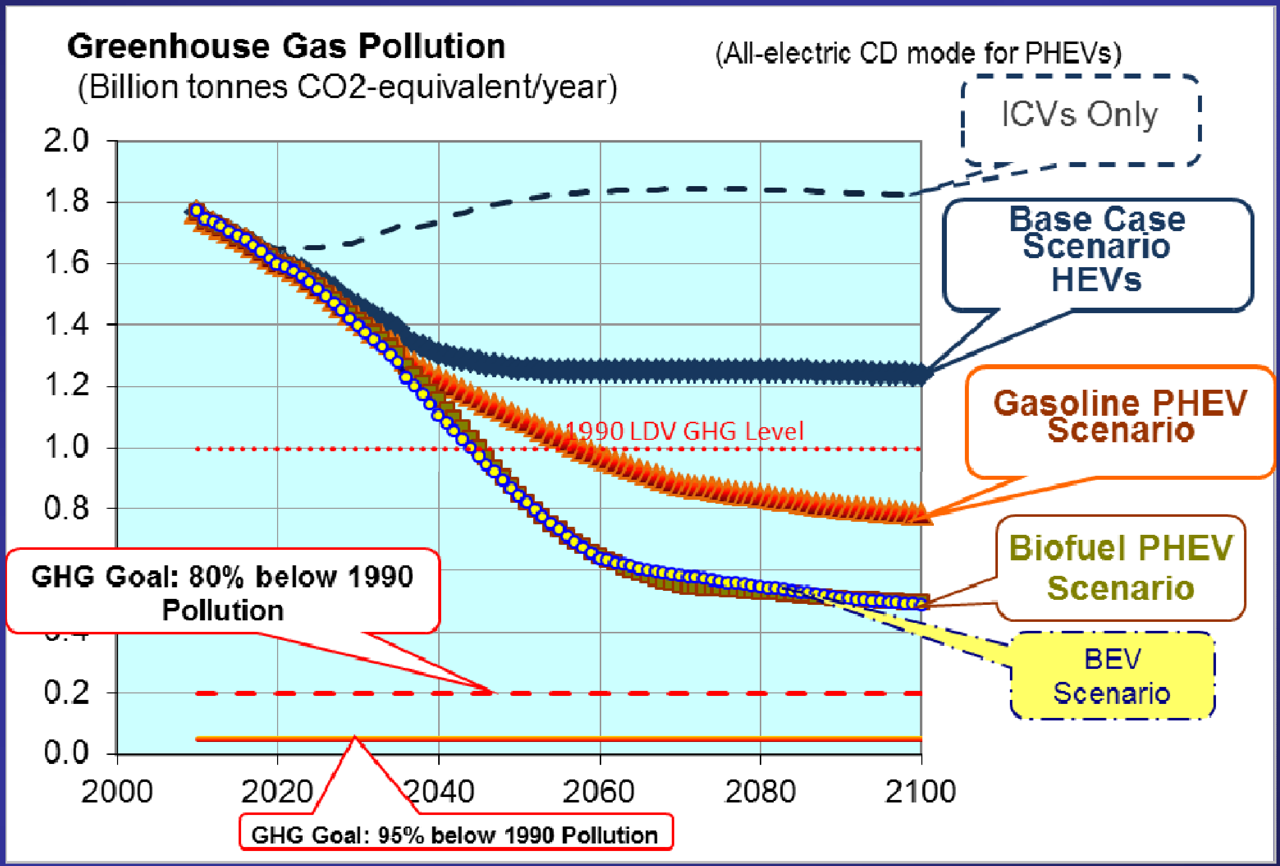
GHGs with Gasoline PHEVs



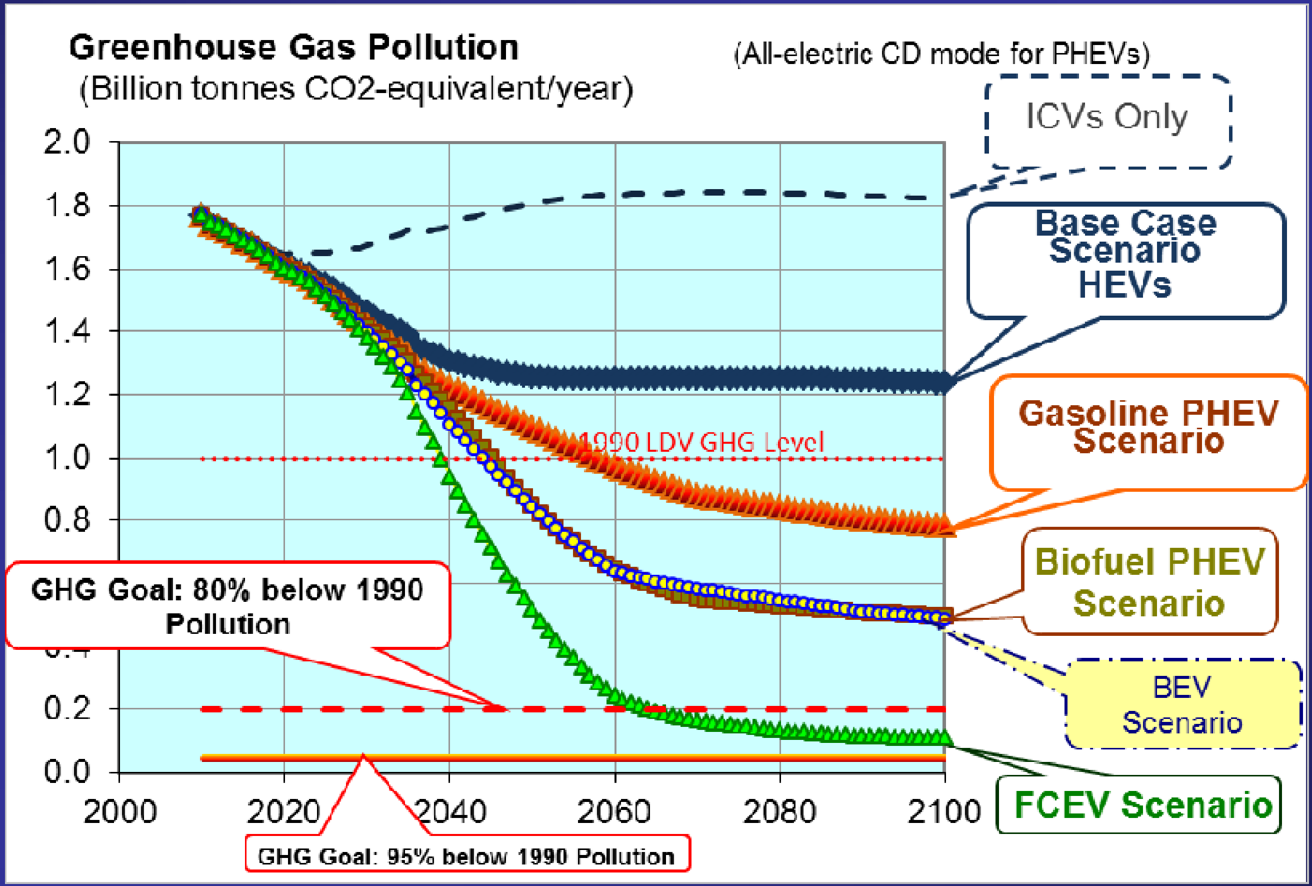
GHGs with Biofuel/Ethanol PHEVs



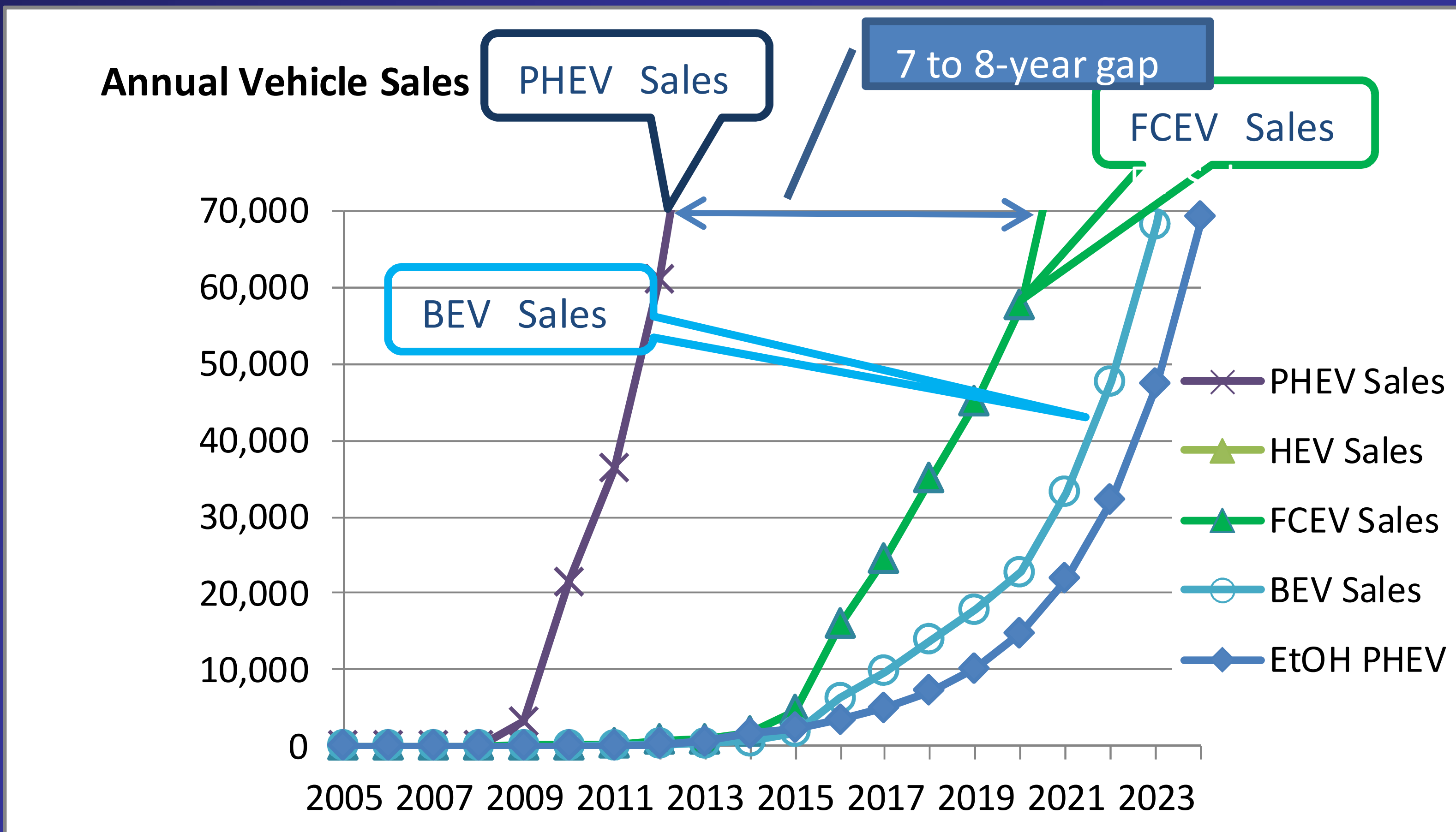
GHGs with BEVs



GHGs with FCEVs

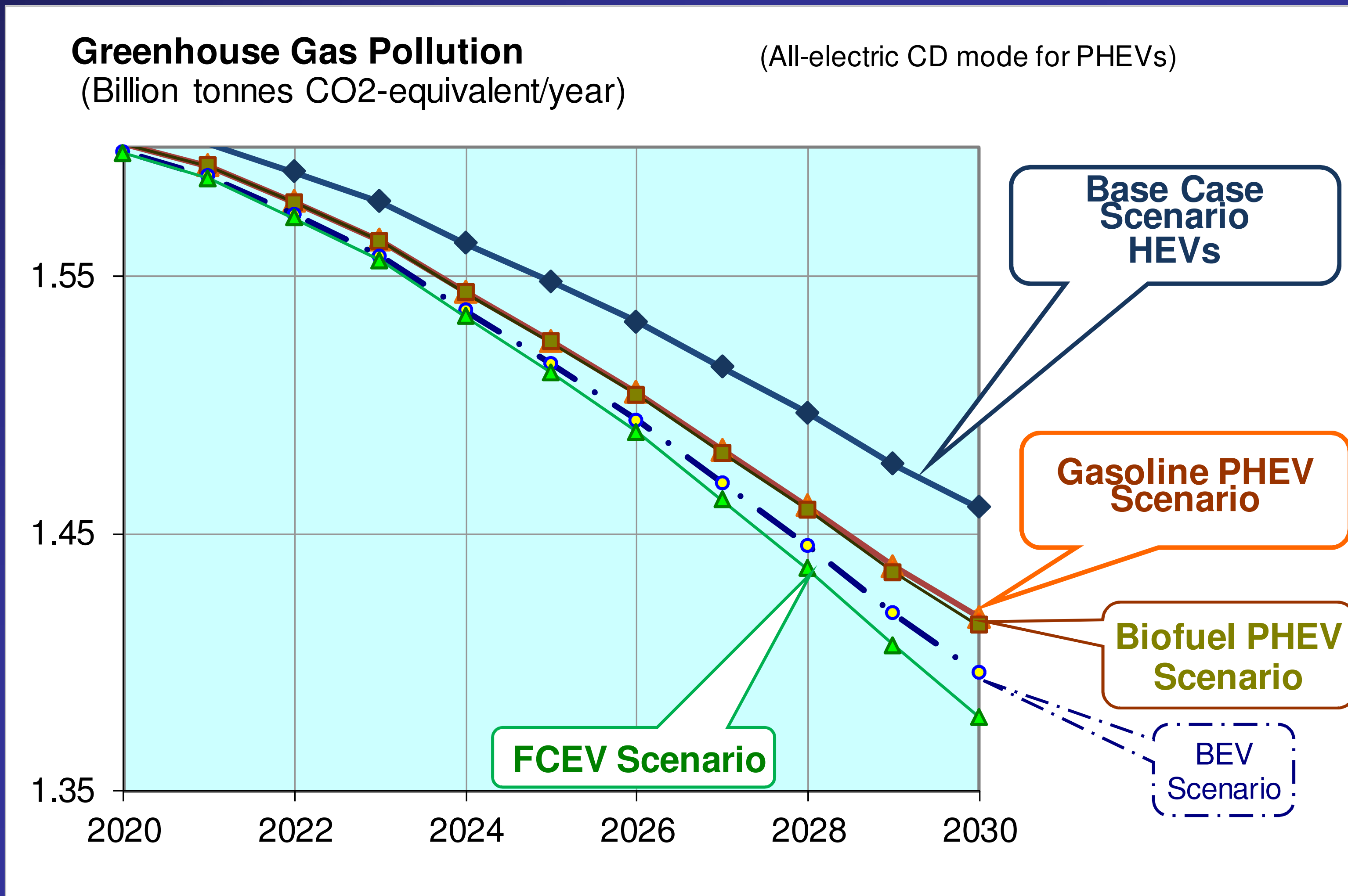


Early AFV Sales



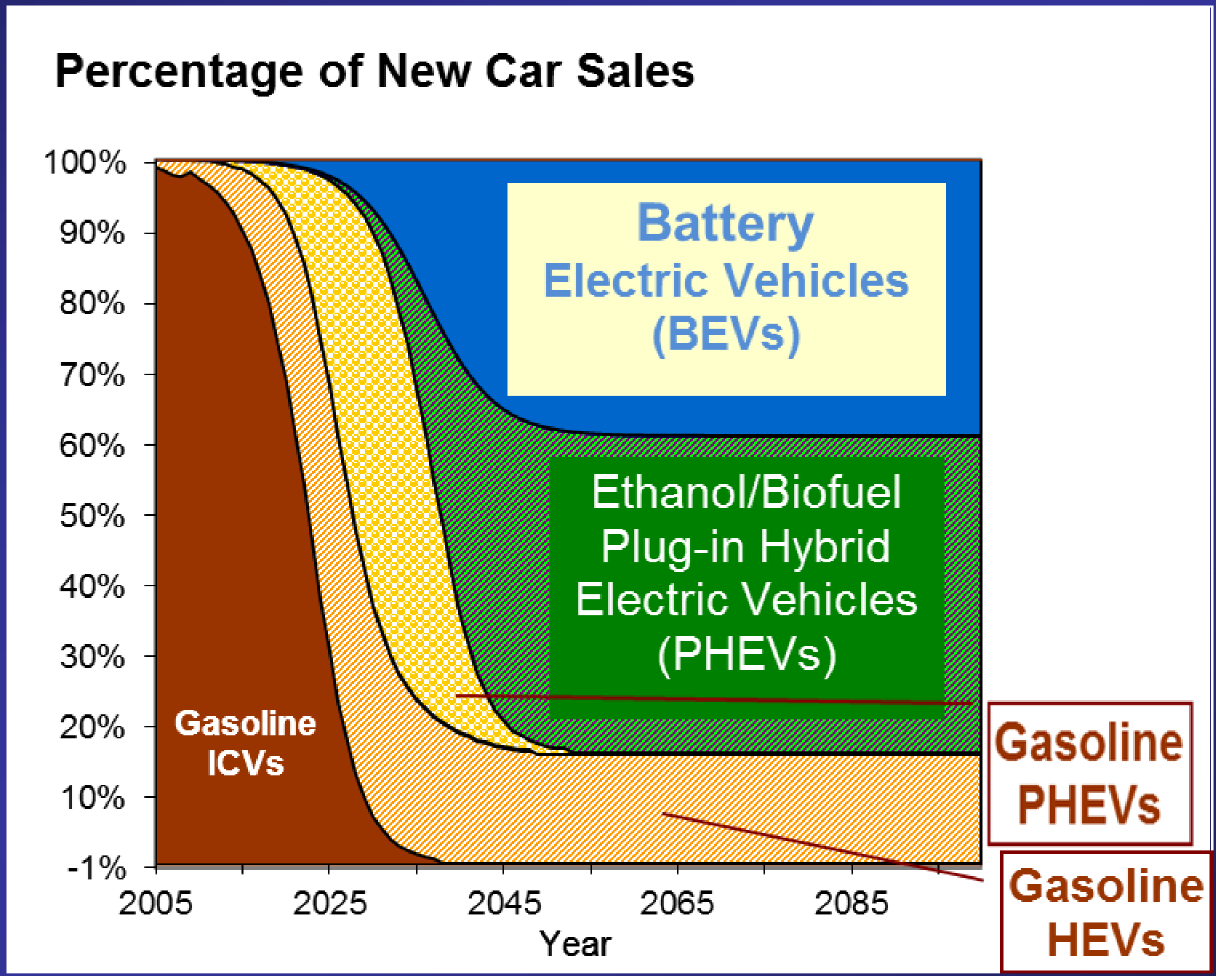
Story Simultaneous.XLS; Tab 'afv SALES'; V 59 10/12 /2011

Early GHGs (2020 to 2030)

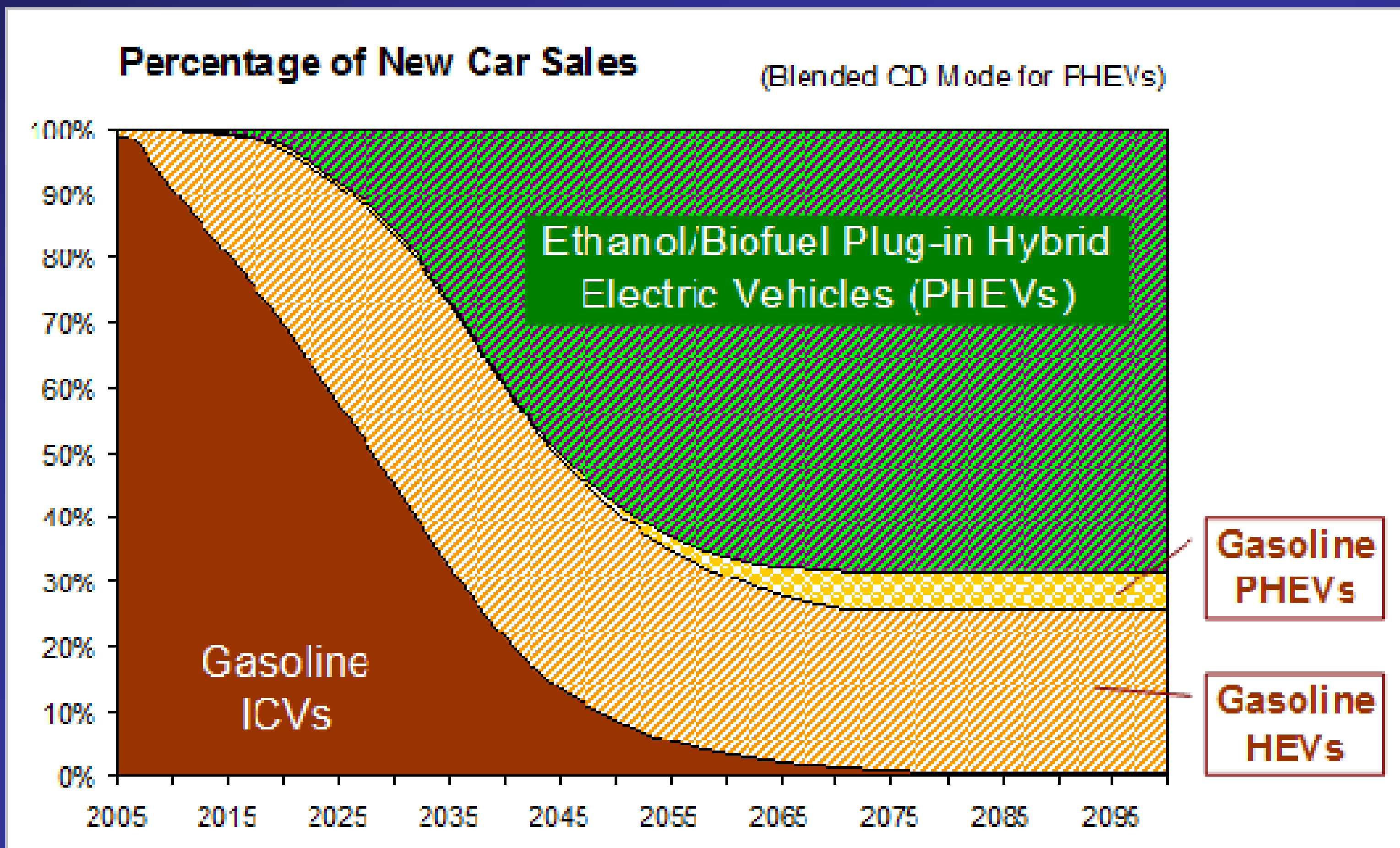


Story Simultaneous.XLS; Tab 'New charts'; Q 370 10/26 /2011

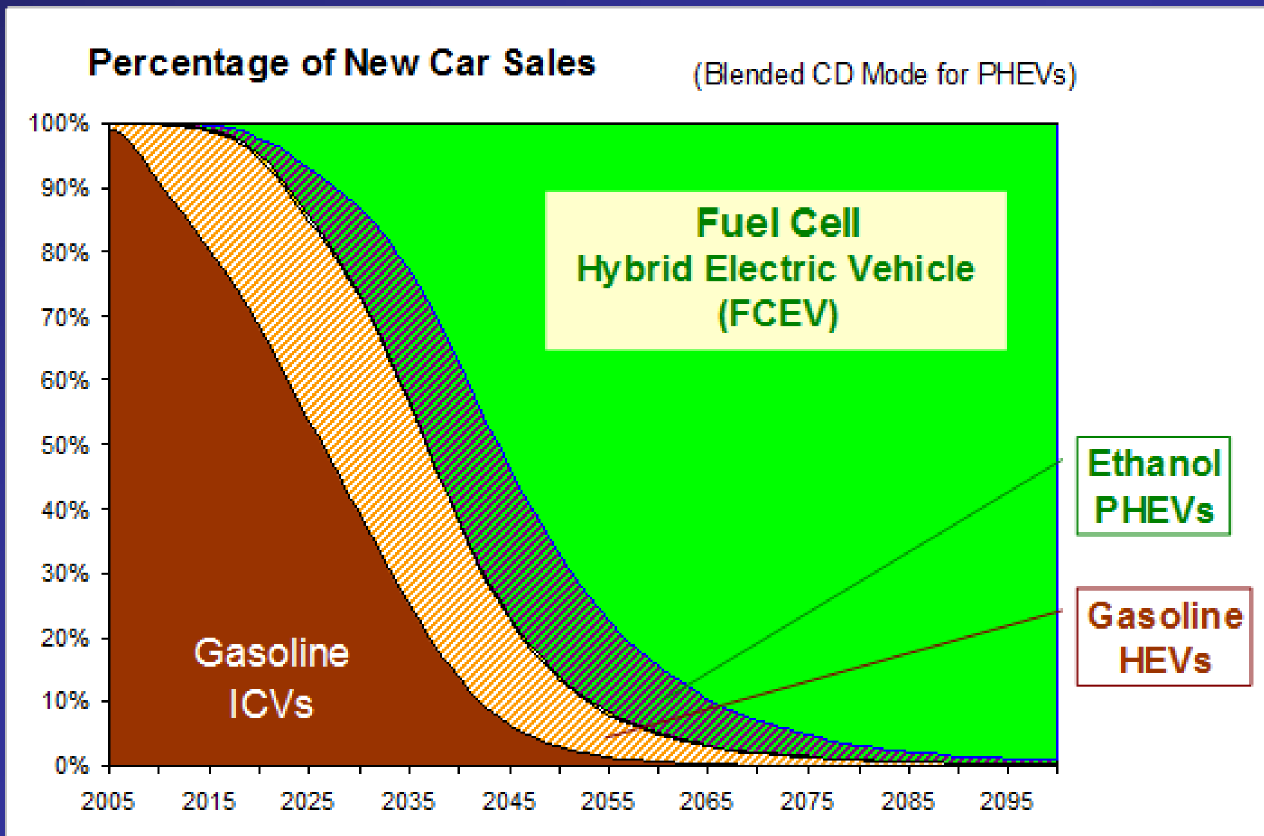
BEV Scenario



Biofuel/Ethanol PHEV Scenario vehicle sales mix

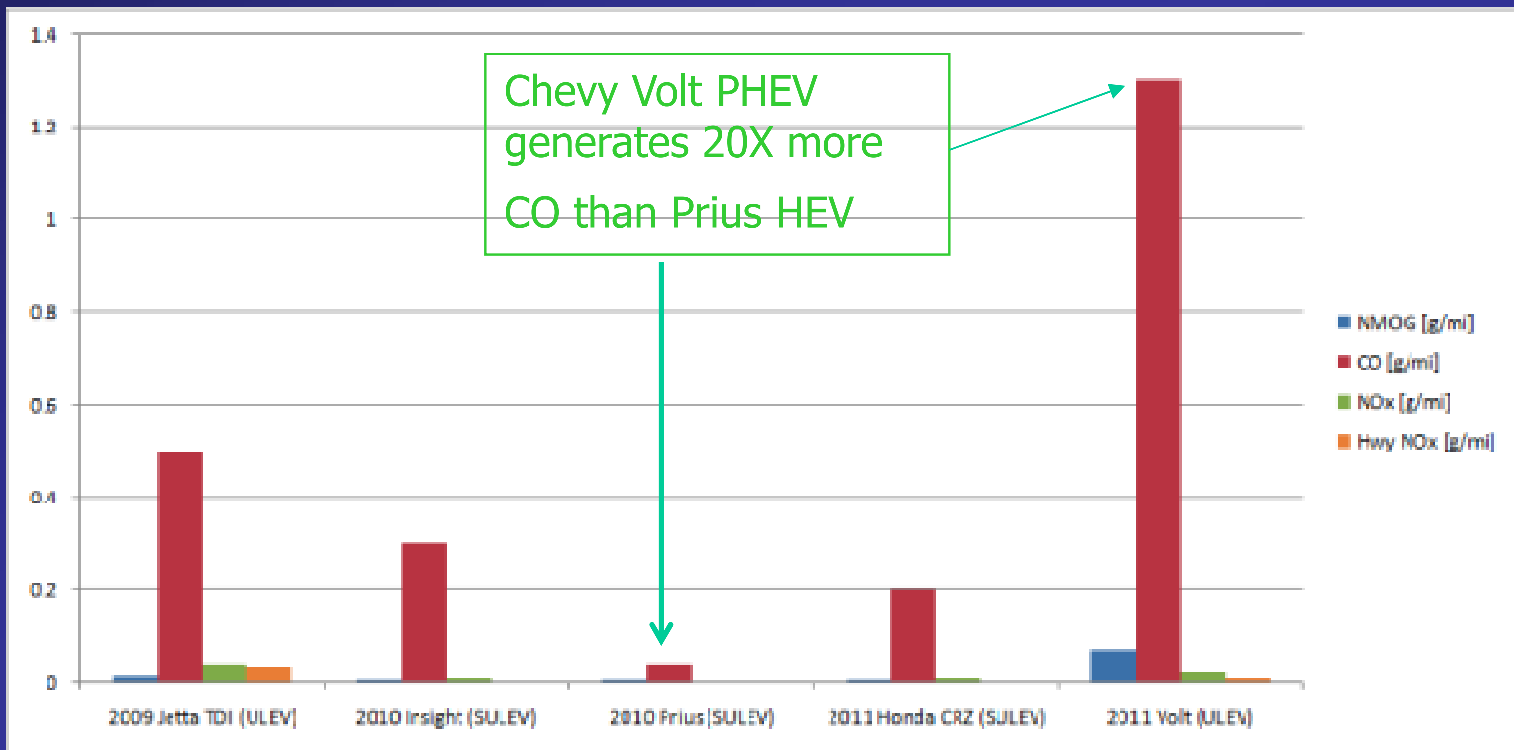


FCEV Scenario vehicle mix



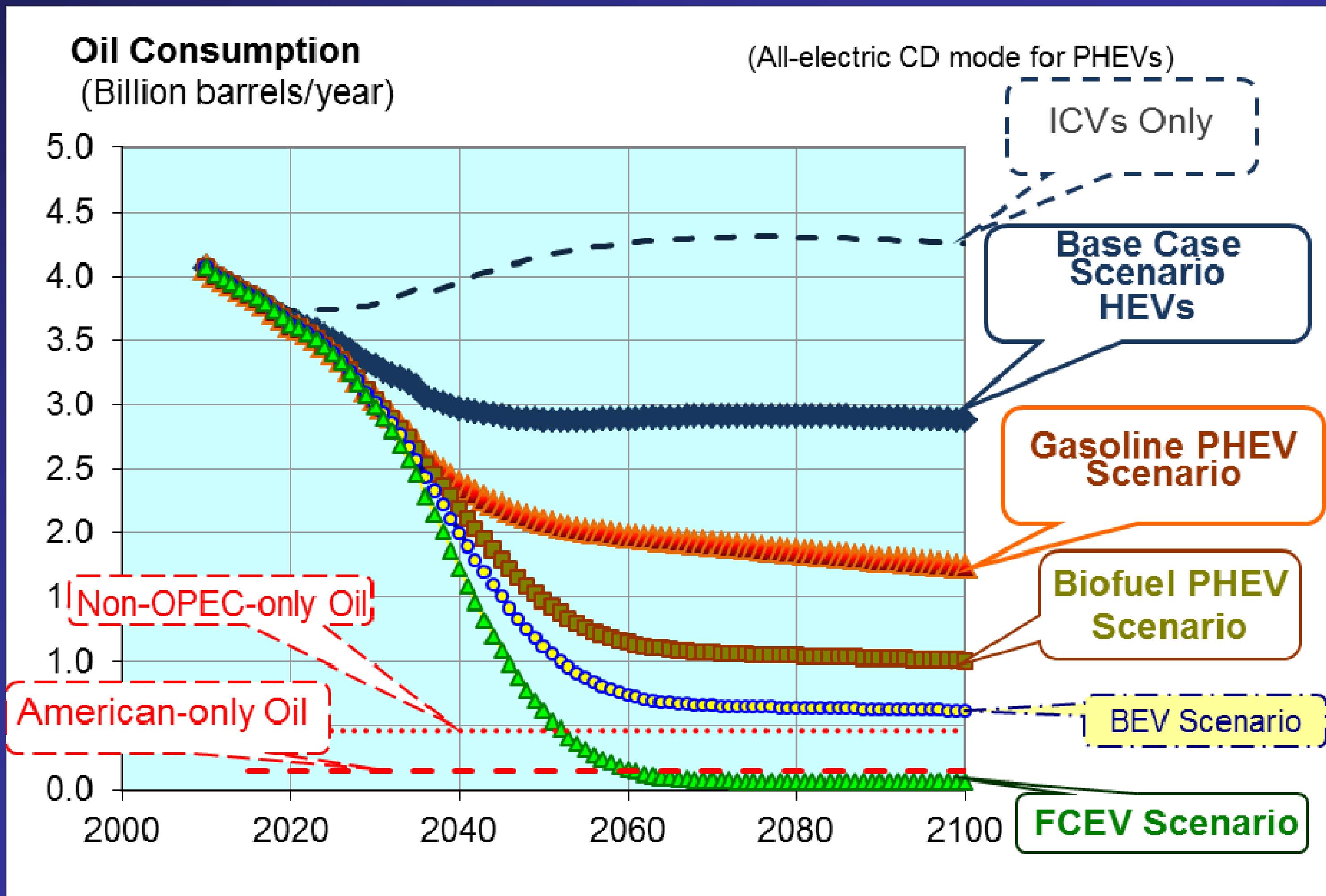
Local Air Pollution

CARB Local Air Pollutant Emissions: PHEV vs HEV (Prius)



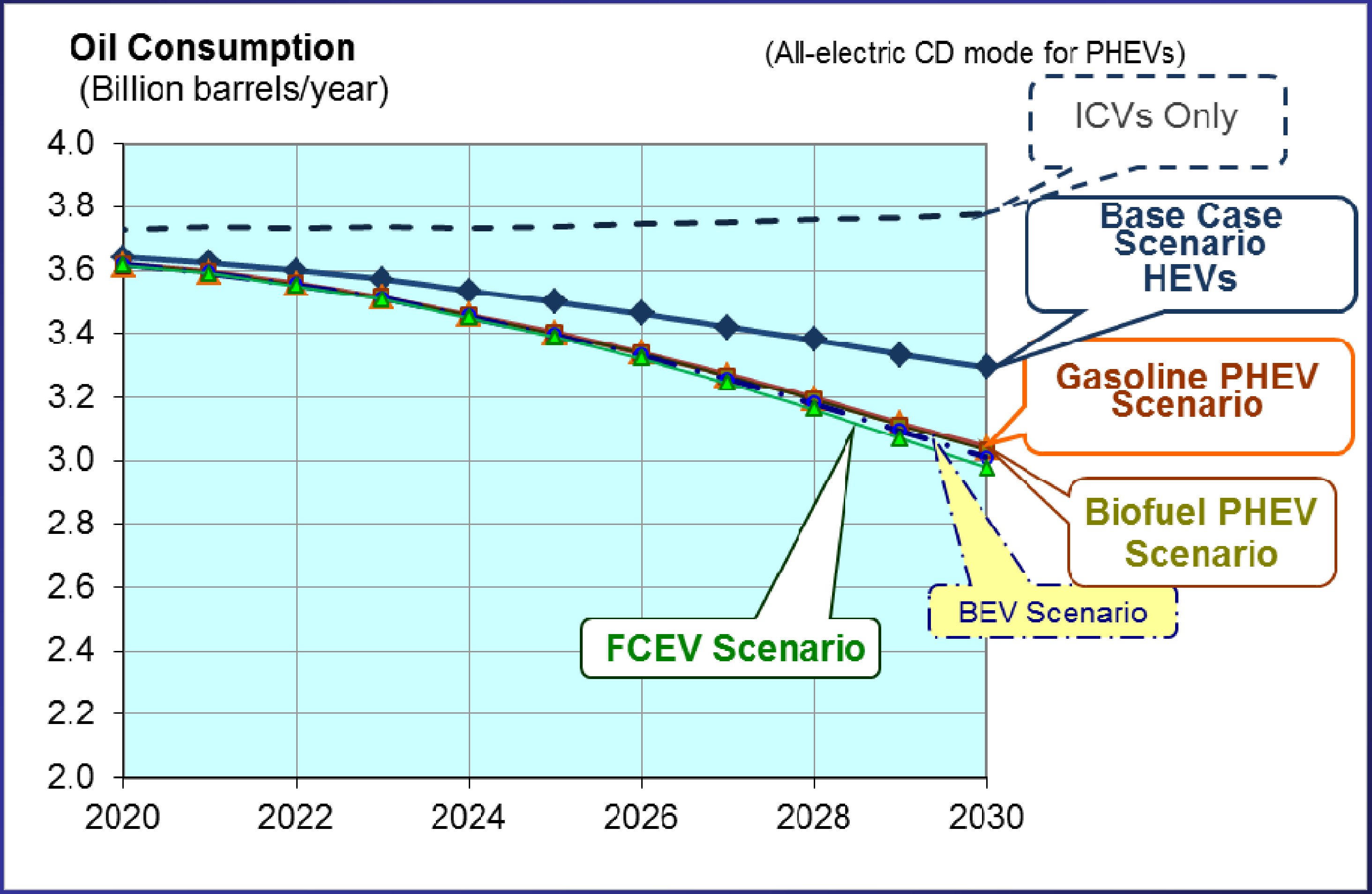
Petroleum Consumption

Oil Consumption



Sources: Argonne National Laboratory GREET 1.8a, AEO 2011 & NHA models

Near-term oil consumption



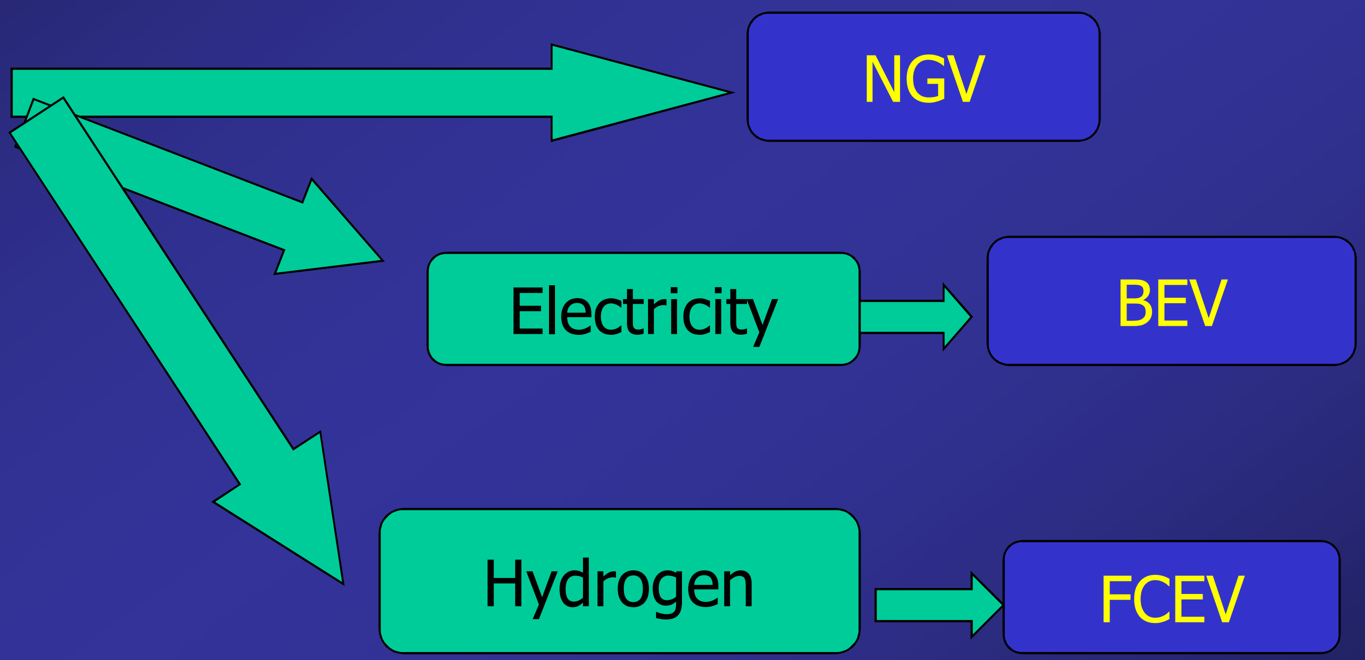
Near-Term Alternative Vehicle Attributes

	Incremental Vehicle Cost (2030-MIT)	Fuel infrastructure Cost per vehicle	Market Penetration Potential	GHG Emission Reductions	Oil Consumption Reductions
PHEV-40	$ 5,000	$ 20,700	100.0%	-25%	-53.5%
BEV-200	$ 10,200	$ 20,700	36.9%	-8%	-24.5%
FCEV-350	$ 3,600	$ 3,200	100.0%	-51%	-99%

Story Simultaneous (Rev B).XLS; Tab 'New charts'; Y 359 10/29/2011

Natural Gas Utilization

- NG



Natural Gas Utilization

		Miles Traveled	Miles Traveled	GHGs (gr/mile)	GHG Ratio	GHG Ratio
NG=>ICV (NGV)		1	0.78	316	1.00	1.25
NG=electricity=>BEV		1.28	1.00	252	0.80	1.00
NG=>H2=>FCEV		2	1.56	197	0.62	0.78

Market Survey

Which EV would you buy?

- EV #1 has a DOE certified range of 431 miles before refueling with an average refueling time of 4.4 minutes

- EV#2 has an EPA-certified range of 73 miles and a refueling time between 7 to 20 hours.

EV #1

- 431 miles range & 4.4 minute refueling
- The Toyota FCHV Highlander (SUV) fuel cell EV

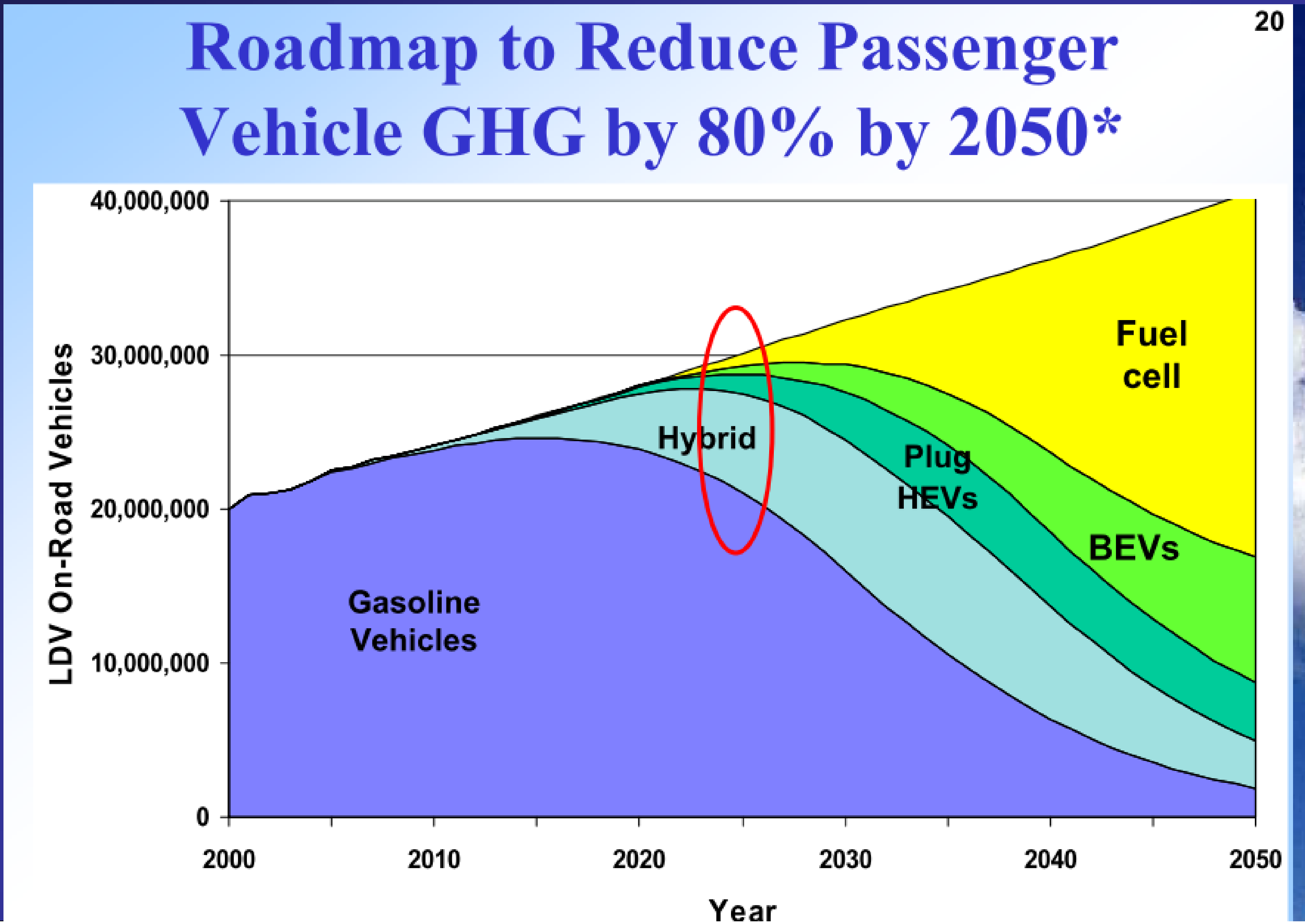
Takeshi Uchiyamada, executive vice president of Toyota Motor Corp: “I have high expectations for fuel-cell vehicles as a candidate for next-generation cars,” Uchiyamada said this week in an interview at the North American International Auto Show in Detroit. “Over the past several years, we’ve seen many of the outstanding technical issues solved.”
Jan 13, 2011

EV #2

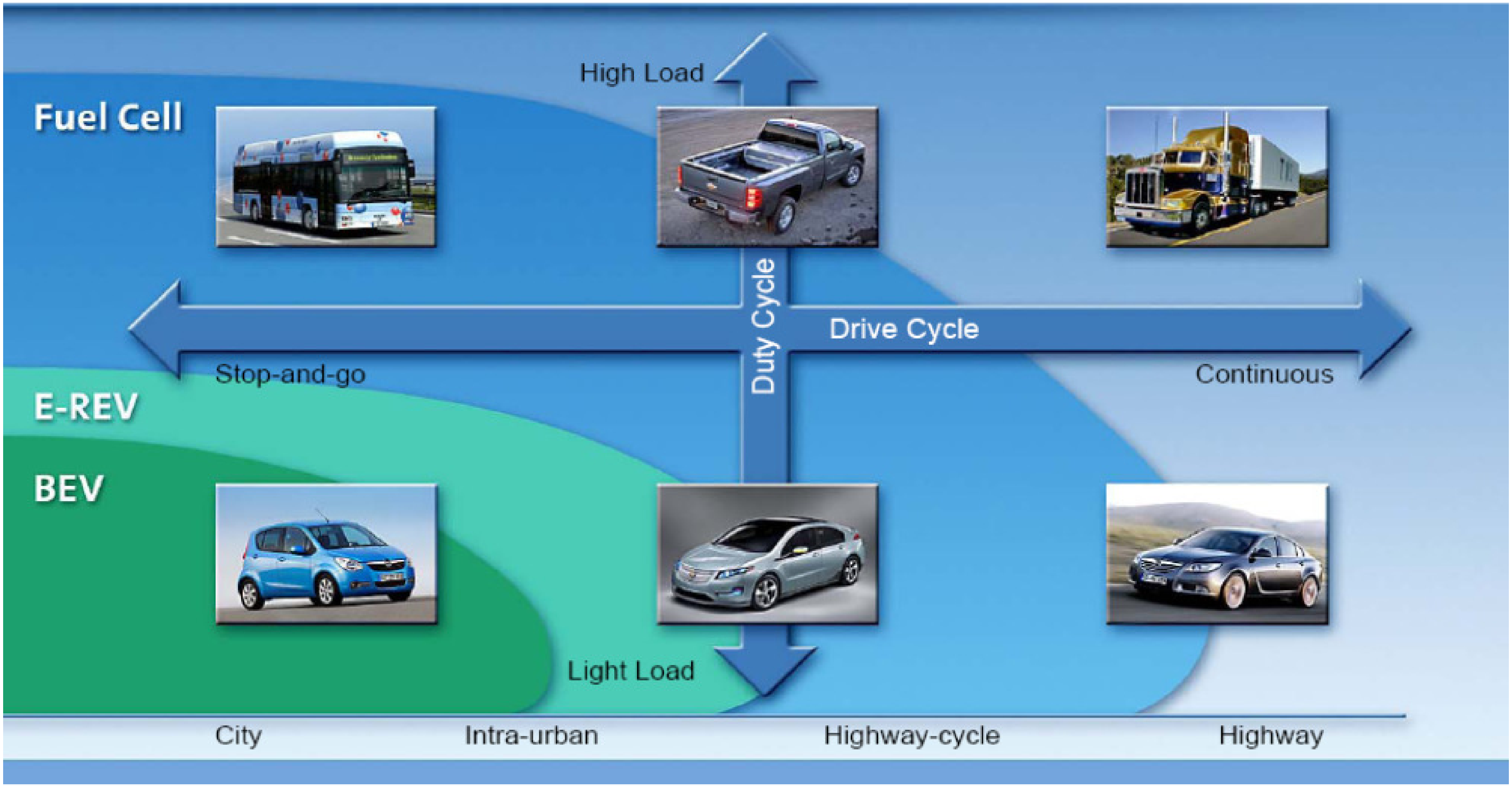
- 73 miles range and 7 to 20 hour refueling
- The Nissan Leaf battery EV:

. Nissan-Renault CEO Carlos Ghosn:
"Zero emissions will not come with hybrids -- they will be fueled initially by batteries and eventually by batteries and fuel cells. The CEO predicted that fuel cells will be part of the automotive picture "within the next ten years." 6/14/2011

CARB's Vehicle ROADMAP (Source Tom Cackette)



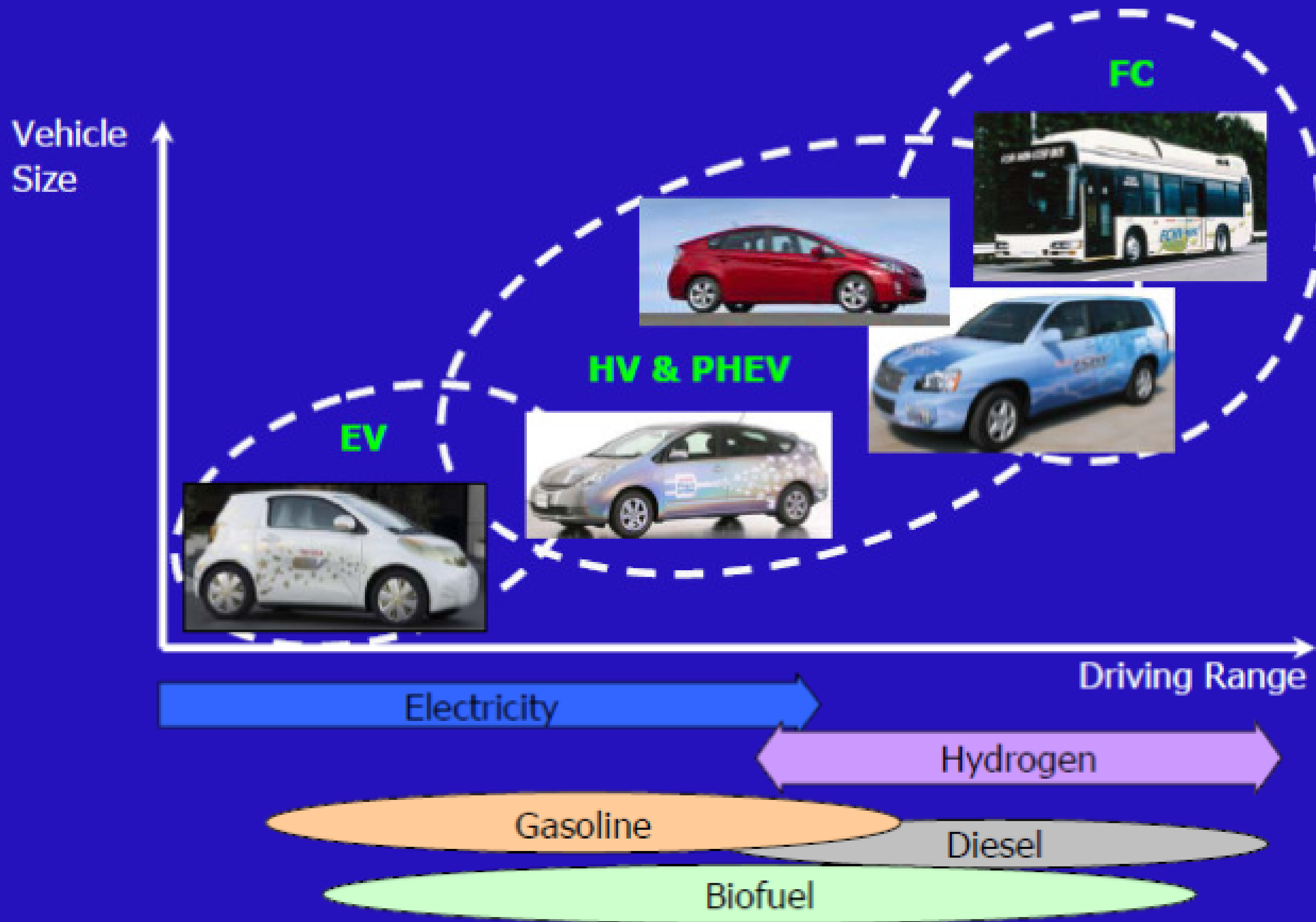
Application Map for Electric Vehicle Technologies



No Silver Bullet !!!

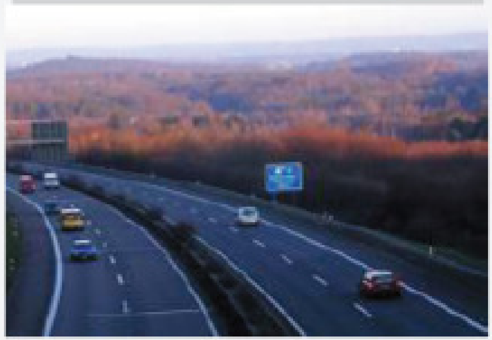
Toyota View of Alternative Vehicle Space:

Market Segments for Each Technologies



Drivetrains for Various Driving Cycles

Long Distance



Suburban

Urban

- Combustion Engine
- Hybridization
- Plug-In/Range Extender
- Electric Drive with Battery
- Electric Drive with Fuel Cell

➢ **Only fuel cell technology is suited equally for both, short and long distance mobility**

Conclusions

- We need a portfolio of alternative vehicles to meet our energy security and environmental goals
- It is too early to "pick winners and losers"
- (especially if the best option is eliminated from consideration!)

Thank You

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thomas@cleancaroptions.com

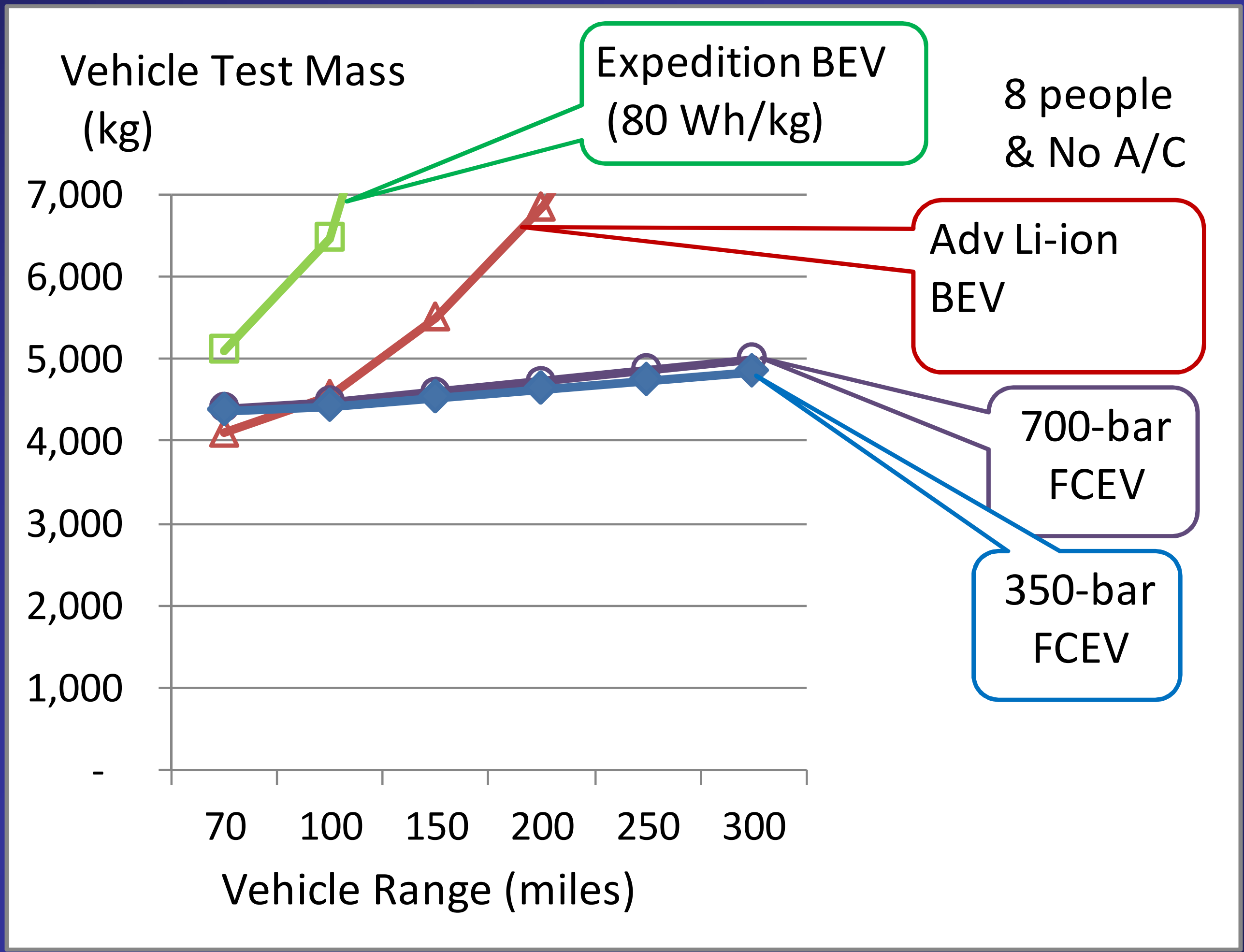
  - Simulation details at:
  - **http://www.cleancaroptions.com**

Back-up Slides

Large (SUV) BEVs

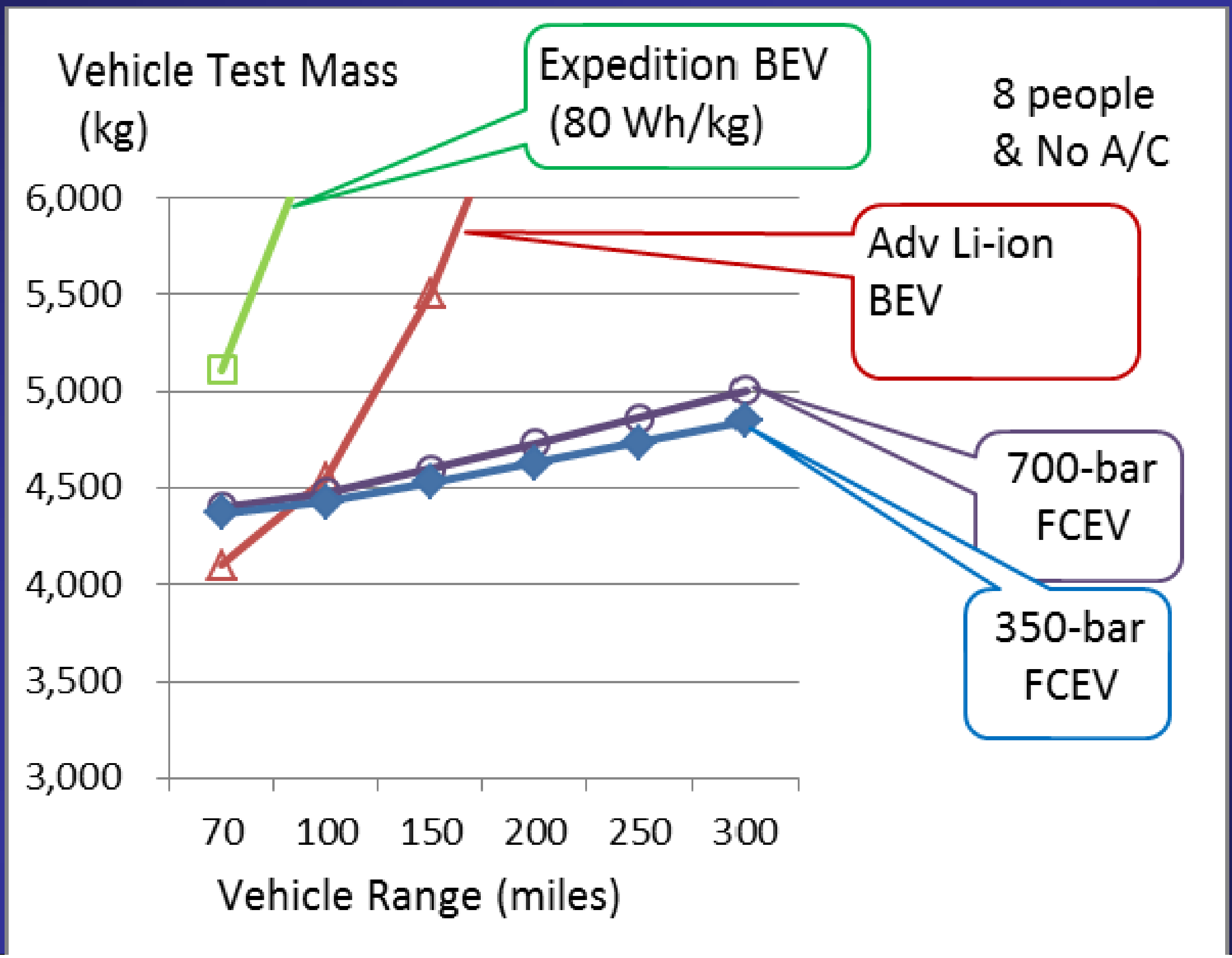
- Ford Expedition:
  - Curb mass = 2631 kg – 501 kg for powertrain, fuel & exhaust systems – 2,130 kg basic glider w/o battery and motor controller system [vs. 1521 kg for the Leaf sedan.]

Expedition size BEV & FCEV test masses vs. range

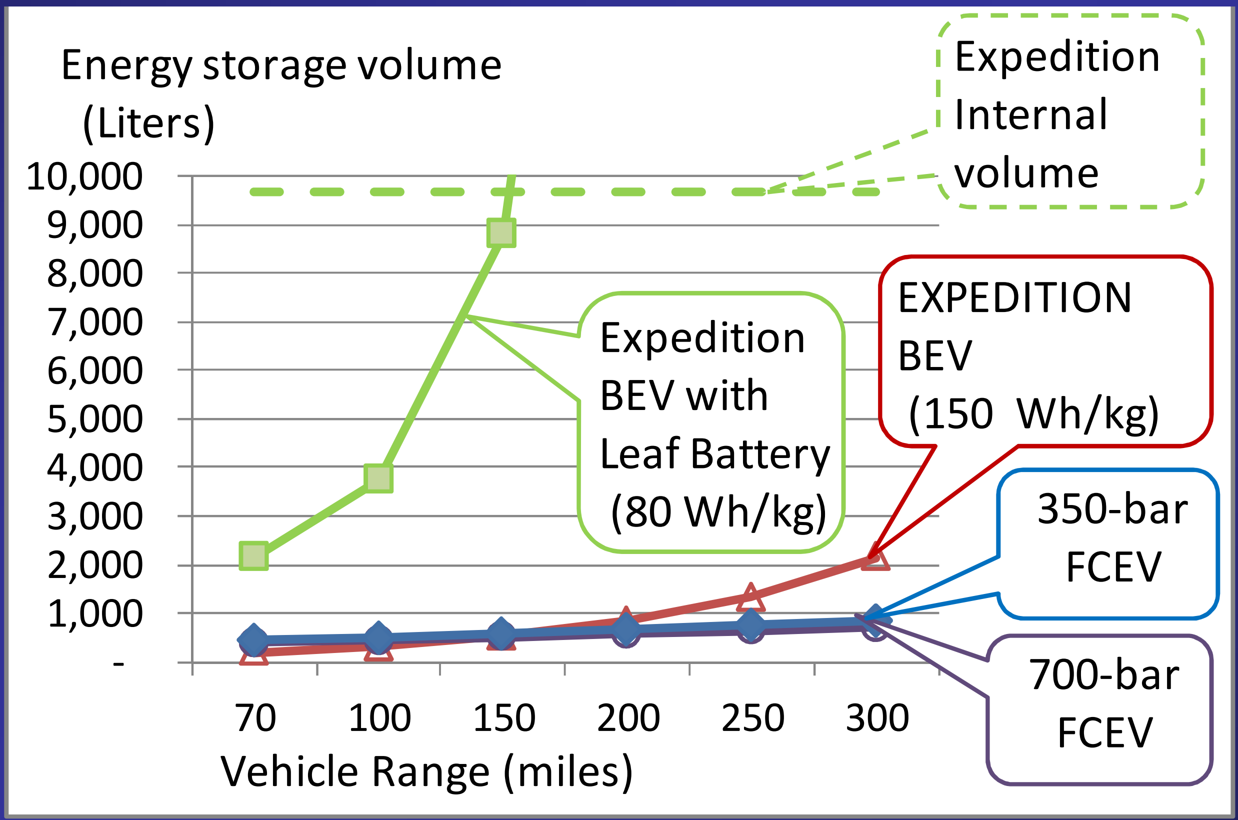


BPEV mass,vol,cost vs range charts RevB.XLS; Tab 'Equation-Expedition'; BS58 - 10 / 9 / 2011

Expanded Scale vehicle test masses for Expedition size SUVs



Energy storage volumes for SUV-size BEVs and FCEVs



BPEV mass,vol,cost vs range charts RevB.XLS; Tab 'Equation-Expedition'; BS41 - 10/9/2011

(expedition size BEV uses current Leaf Li-ion battery technology.)

Expanded scale energy storage volumes