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Battery Pack Requirements and Targets Validation

FY 2008 DOE Vehicle Technologies Program Annual Merit Review

Bethesda North Marriott Hotel and Conference Center

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This presentation does not contain any proprietary or confidential information.

Sponsor:
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Topics of Presentation (Outline)

- Purpose –
  - help determine an effective mix of power vs. energy in li-ion battery cells and battery packs, considering market potential of vehicle designs enabled.
- Response to review comments – none, first Merit Review presentation
- Barriers –
  - pressures to incorporate more kWh in packs than consumers will pay for
  - CARB regulation tending to induce higher cost packs
  - need to meet all air quality and emissions requirements
- Approach –
  - utilize best available methodologies to address ability of PHEVs to overcome barriers (engineering, benefit/cost, cost effectiveness, and life cycle analysis)
- Performance –
  - appropriately affect general level of support for PHEV technology
  - private and public R&D funding decisions related to results
  - emphasize fuel savings per kWh of electricity use as effectiveness metric
  - act as unbiased evaluator of claims for benefits of PHEV & EV powertrains

Topics of Presentation (Outline, continued)

- Accomplishments/publications –
  - May 2006 OVT PHEV kickoff meeting: PHEV overview presentation
  - July 2006 House Science Committee testimony
  - Oct. 2006 One EVS 22 paper
  - Several invited presentations
  - Dec. 2007, Three EVS 23 papers
  - Jan. 2008, Completed PHEV subtask of IEA HEV/EV IA hybrid study
- No patents, no technology licenses
- Ongoing methodology development, transfer
  - Developing evolutionary refinements to GREET life cycle methodology for specific case of PHEV – focus on charge depletion behavior
  - Critically evaluating the “utility factor” as a basis for determining “miles electrifiable”
- Plans for FY 2008 (partial list)
  - Begin detailed evaluation of recycling and/or reuse of batteries
  - Give papers and presentations on key study topics and findings
  - Complete comprehensive study of PHEVs, City EVs with EPRI

- Purpose - help determine an effective mix of power vs. energy in li-ion battery cells and battery packs, considering market potential of vehicle designs enabled.

- Approach –
  - engineering economics
  - benefit/cost and/or cost effectiveness
  - consumer preference modeling (2008+)

- Market potential question # 1, barrier # 1, more kWh than customer can afford
  - If only one PHEV range were selected, would it be better to select a PHEV10, PHEV20, or PHEV40?
  - As charge depleting PHEV range is extended
    - *What happens to net benefits?*
    - *At what point does an entirely new vehicle body have to be designed, and what is the effect on cost?*

Key Potential PHEV Market Entry Barrier 1 – Designing for More Battery Pack Energy (PHEV Range) Than Needed

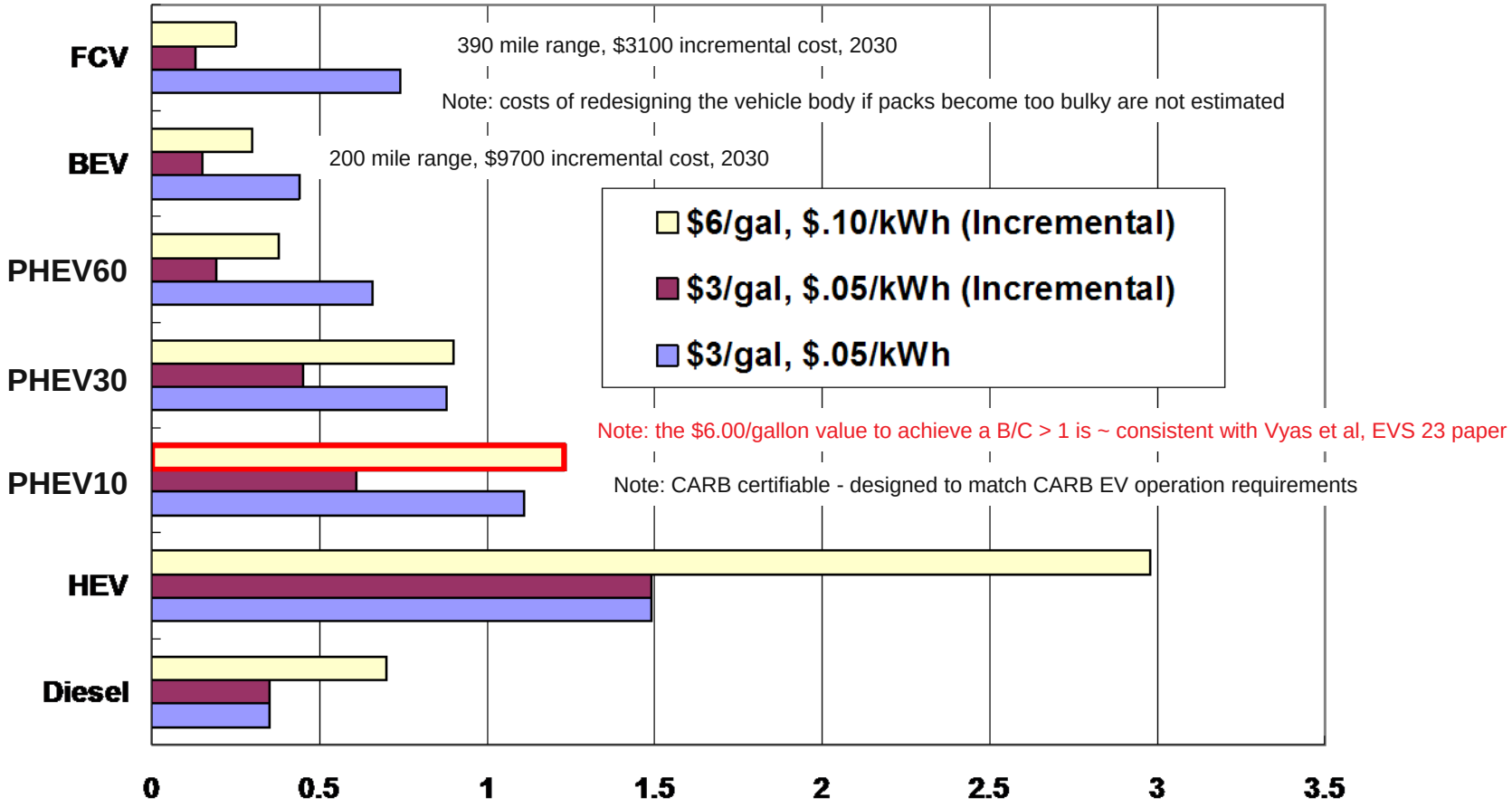
- Fundamental question for initial target market, early PHEV pack goals
  - Start in high cost, low volume performance vehicles and "trickle down". Learn about battery manufacture in low volumes, revise designs, then expand
    - *Tesla roadster*
    - *Chevrolet Volt*
  - Start in reasonable cost, high efficiency, high volume vehicles, then "power up" and add energy (in same pack volume) as batteries improve
    - *Saturn Vue, Ford Escape, Toyota Prius*

- Providing more PHEV kWh than used per normal day
  - Increases battery pack and vehicle cost
  - Increases battery pack volume (reduces storage volume, value to consumer)
  - Increases battery pack mass (increases fuel/electricity use)
  - Decreases potential sales, lowering volume and increasing unit cost
  - Can make vehicle redesign necessary, increasing cost
  - However, if a few enthusiasts want the vehicles, is learning at low volume best?

Symbols on Slides

- HEV = hybrid electric vehicle
- PHEV = plug-in hybrid
- PHEV## = plug in hybrid with range of ## in miles (km on some slides)
- FCV = fuel cell vehicle
- BEV = battery electric vehicle
- VMT = vehicle miles of travel
- W = watts
- Wh = watt-hour - power of a watt continuing for an hour, a measure of energy
- kWh = kilowatt-hour (1000 Wh)
- CD = charge depletion
- CDE = charge depletion all electrically
- CDB = charge depletion in blended mode
- Blended = the engine comes on intermittently as the battery discharges
- Li-ion = lithium ion (battery type, may refer to different chemistries across slides)
- Ni MH = nickel metal hydride (battery type)

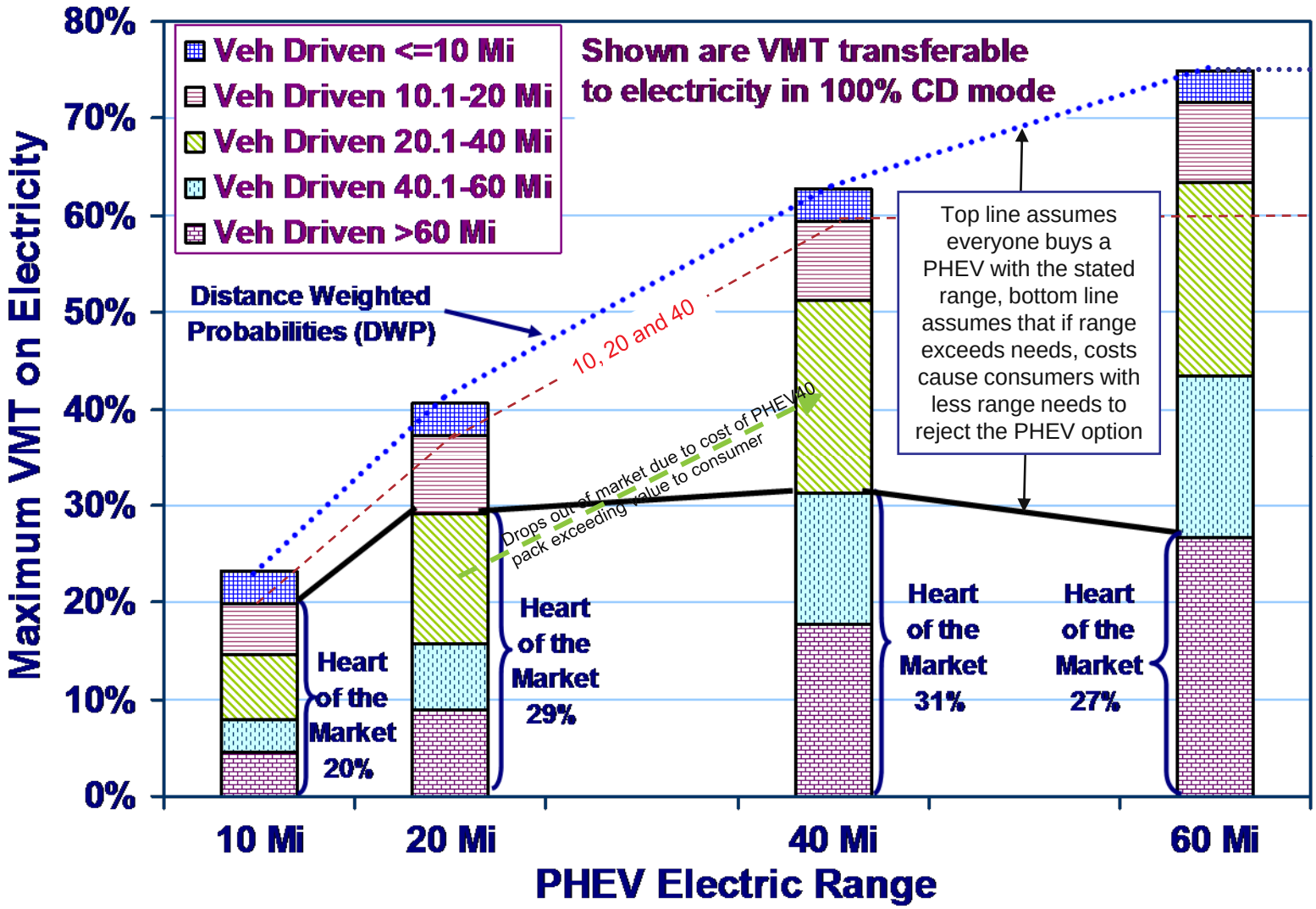
Barrier 1 – For Average Driving, MIT's Recent Study Implies Adding EV Range Reduces Benefit/Cost Ratios



Note: the PHEVs characterized are designed to operate all electrically on the UDDS. Blended mode should be more cost effective, will be studied in '08

From "Where is the Early Market for PHEVs" presentation given at EVS-23 (corrected) by D. Santini, Dec. 2007. Derived from data in Kromer and Heywood, 2007 "Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet. MIT LFEE-2007 03 RP.

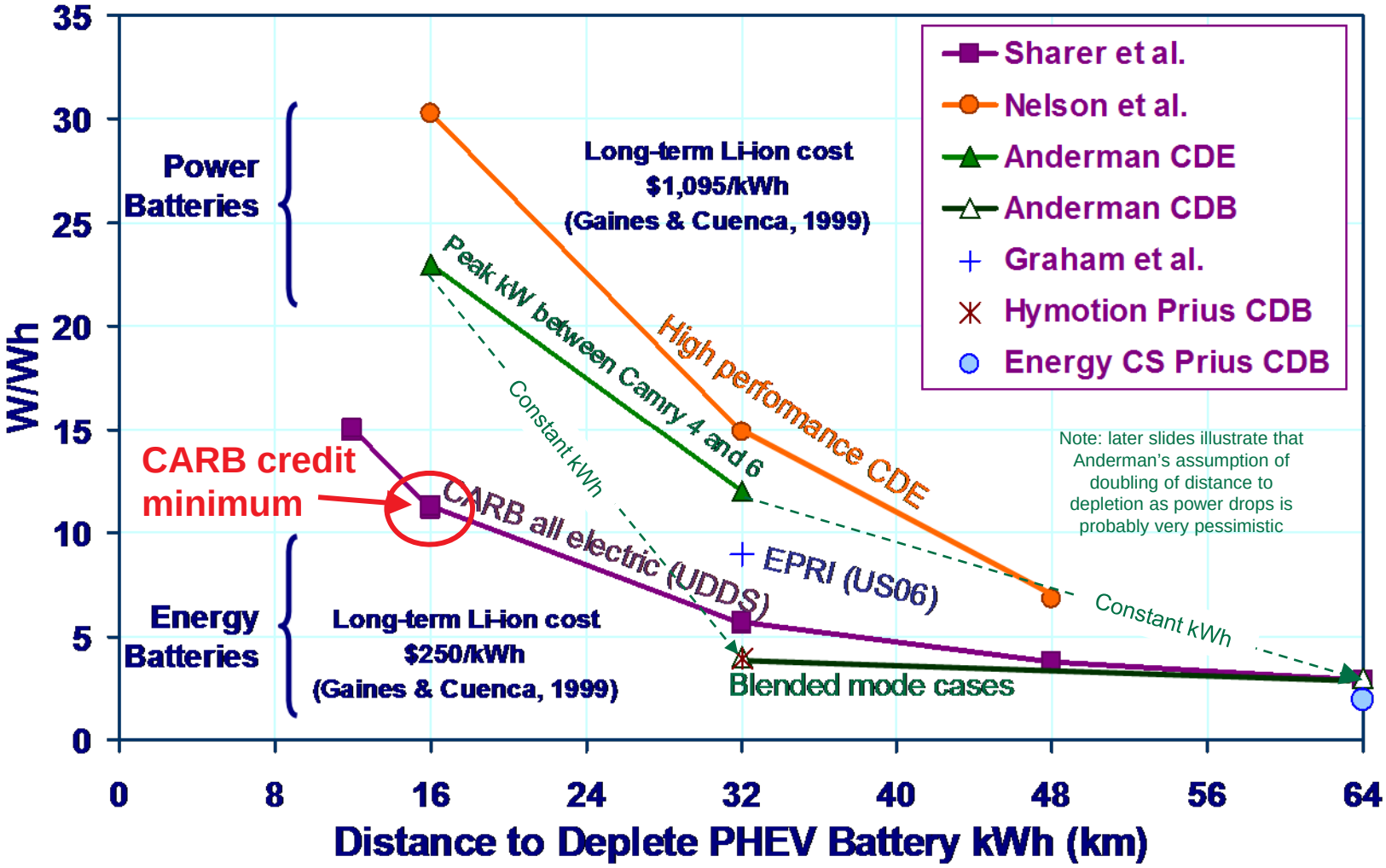
Market Potential – a "Universal" PHEV40 Design May Save No More Fuel Than a PHEV20, if Costs Exceed Consumer Value



Key Potential PHEV Market Entry Barrier 2 – Regulatory Requirement for More Battery Pack Power than Needed

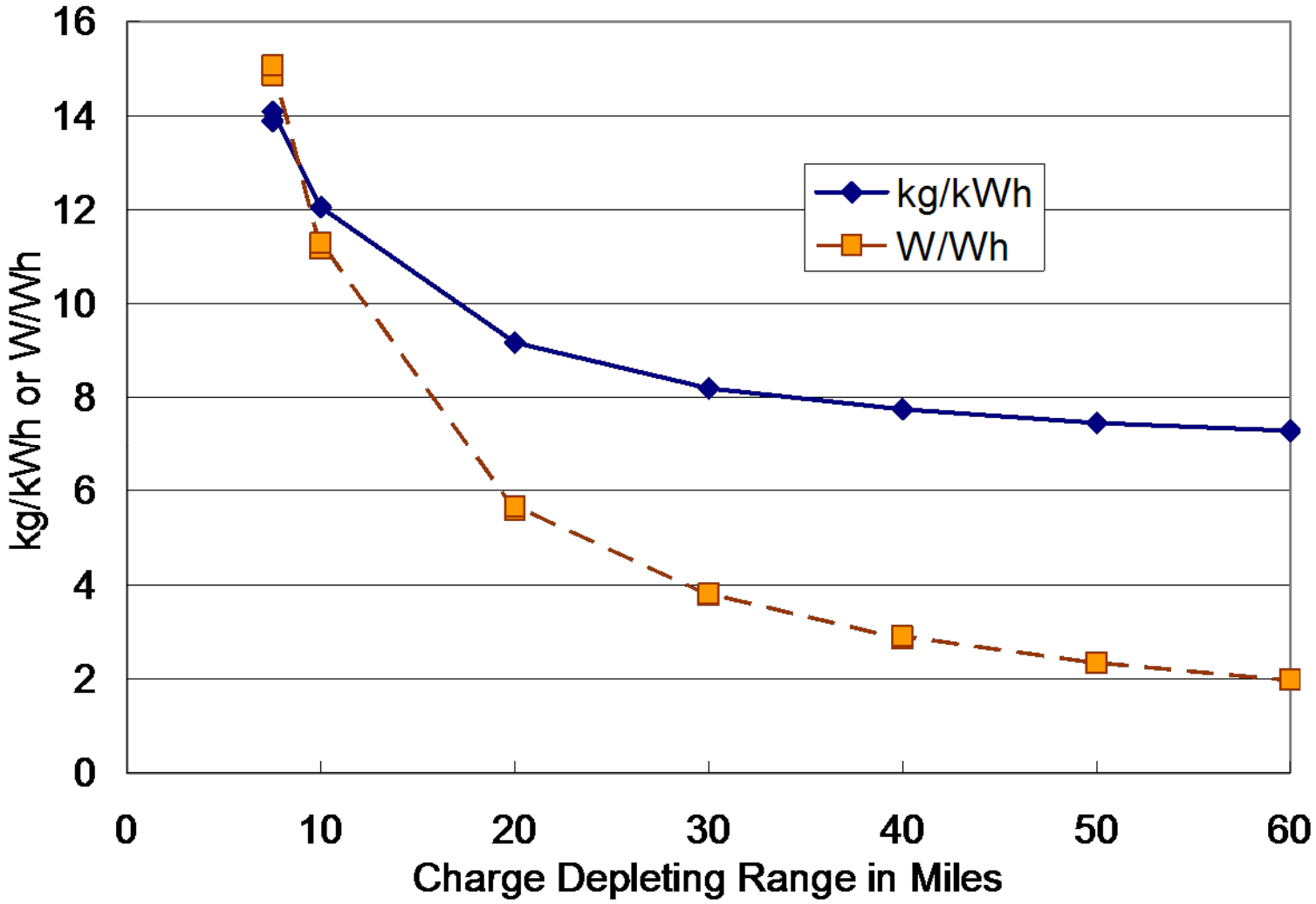
- CARB currently provides LEV credit for a PHEV10 meeting UDDS speed/time trace all-electrically (down from PHEV20 in 1990s)
- Argonne PHEV simulations & tests show significant fuel savings per kWh with blended mode for PHEVs unable to meet the UDDS speed/time trace all-electrically
- Requiring high levels of battery pack power:
  - Pushes up costs per kWh
  - Increases cooling requirements, and bulk of packs per kWh
  - Decreases pack gravimetric and volumetric energy density
  - May make PHEVs more marketable to high end consumers

Barrier 2 - Meeting CARB's Credit Minimum May Increase Pack Costs/kWh, Possibly Reduce National kWh Sold



Base data from Vyas et al, "Plug-In Hybrid Electric Vehicles: How Does One Determine Their Potential for Reducing U.S. Oil Dependence" EVS-23 Anaheim CA, Dec. 2007

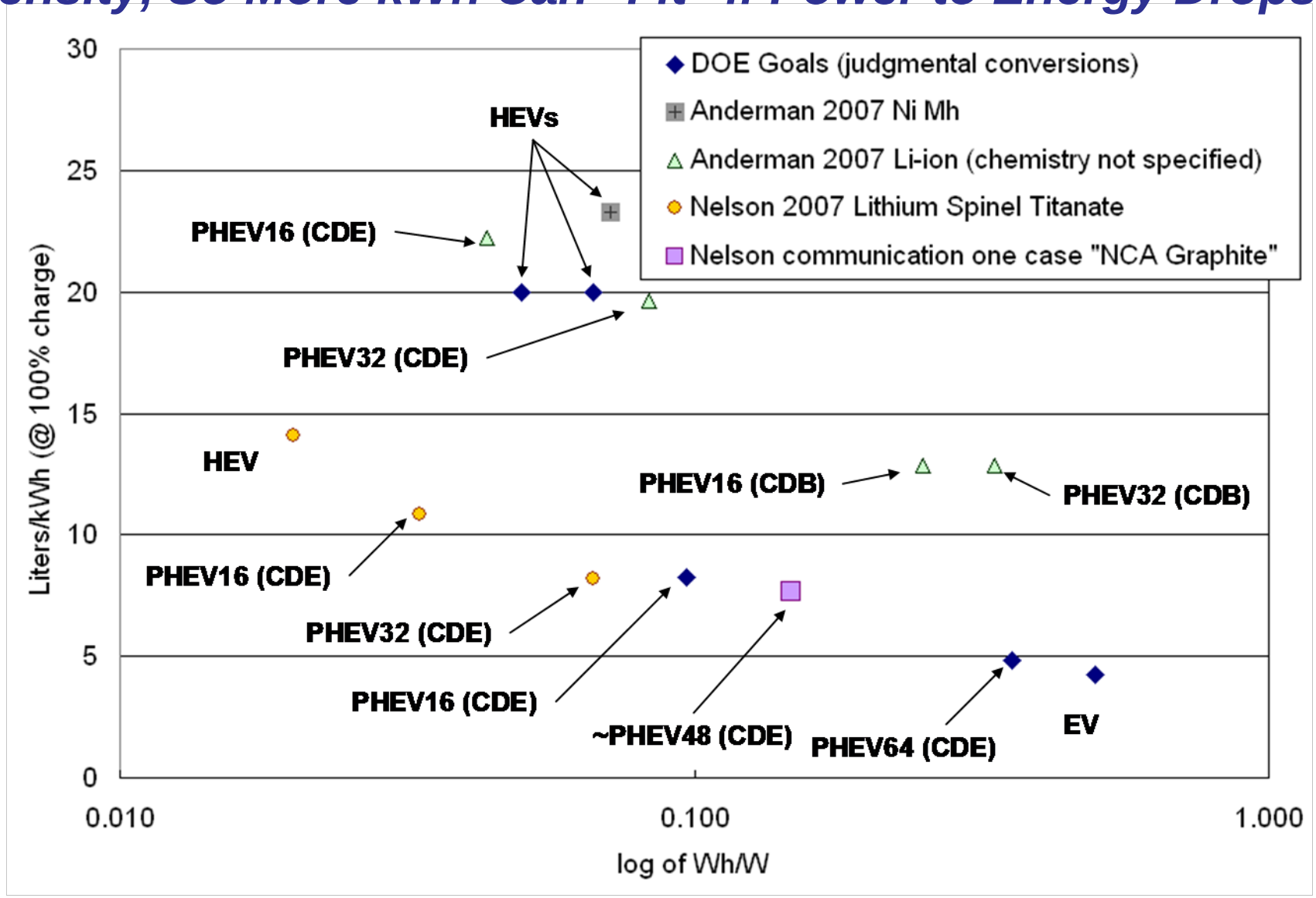
Barrier 2 – Lower W/Wh Results in Less Material per kWh of Capacity, Results in Less Cost per kWh



Based on Sharer et al. See prior slide.

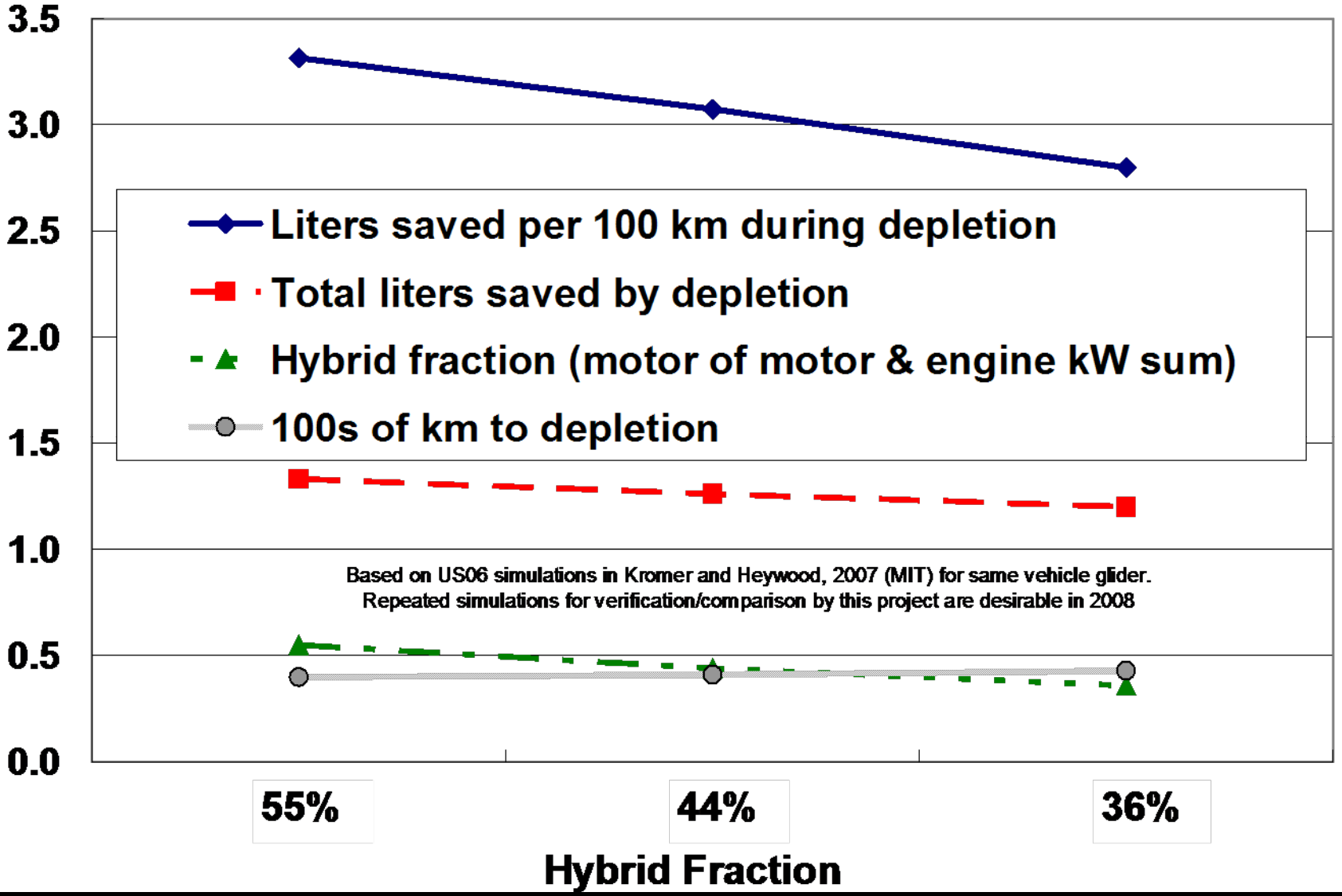
Base data from Sharer et al, Vehicle Simulation Results for Plug-in HEV Battery Requirements. EVS-22, Oct. 23-28, 2006

A Higher Wh/W Ratio Increases Volumetric Energy Density, So More kWh Can "Fit" if Power to Energy Drops

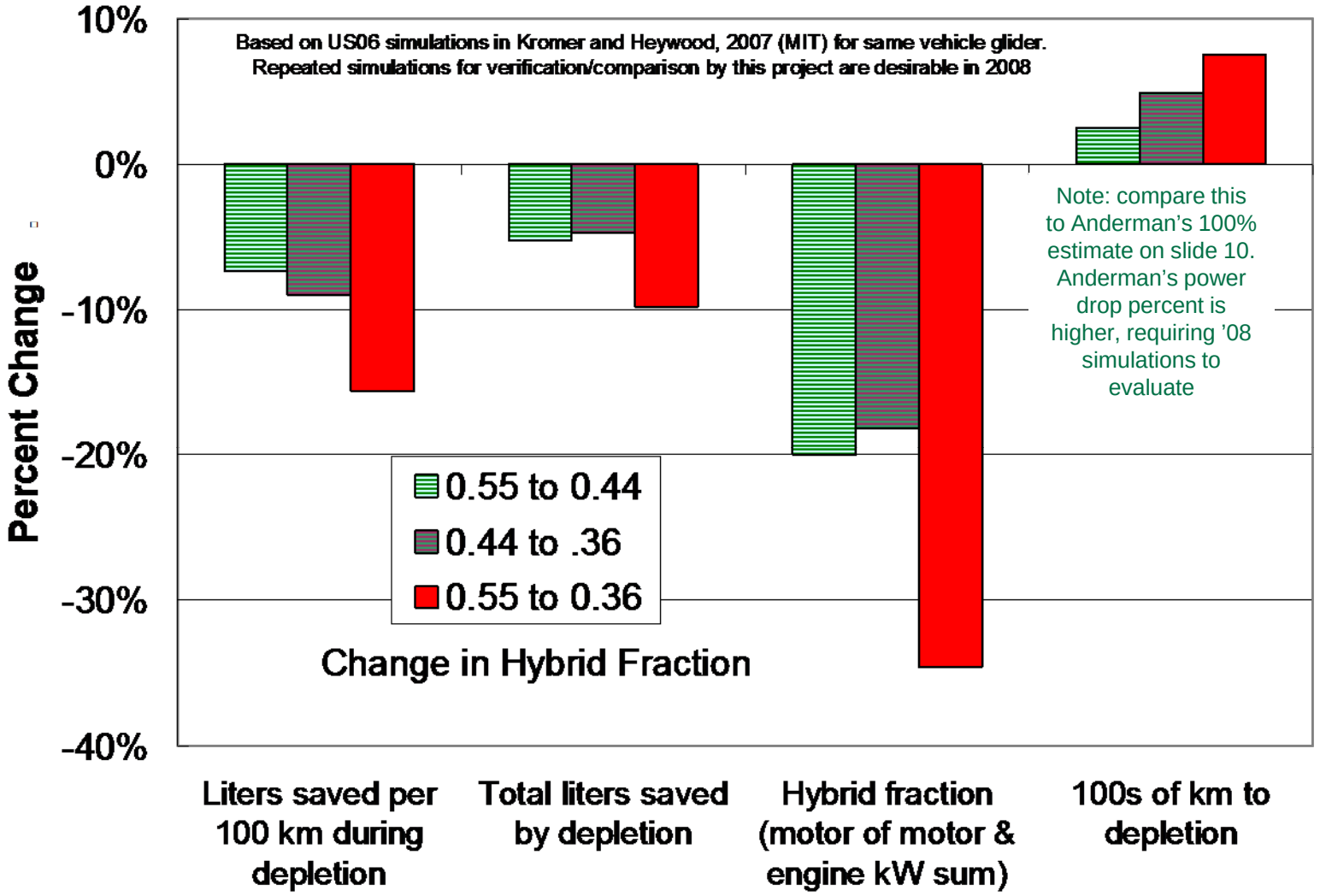


From Vyas et al, "Plug-In Hybrid Electric Vehicles: How Does One Determine Their Potential for Reducing U.S. Oil Dependence" EVS-23 Anaheim CA, Dec. 2007

MIT's PHEV Simulations Imply Power Can be Reduced Sharply With Little Effect on Fuel Saved or Depletion Distance



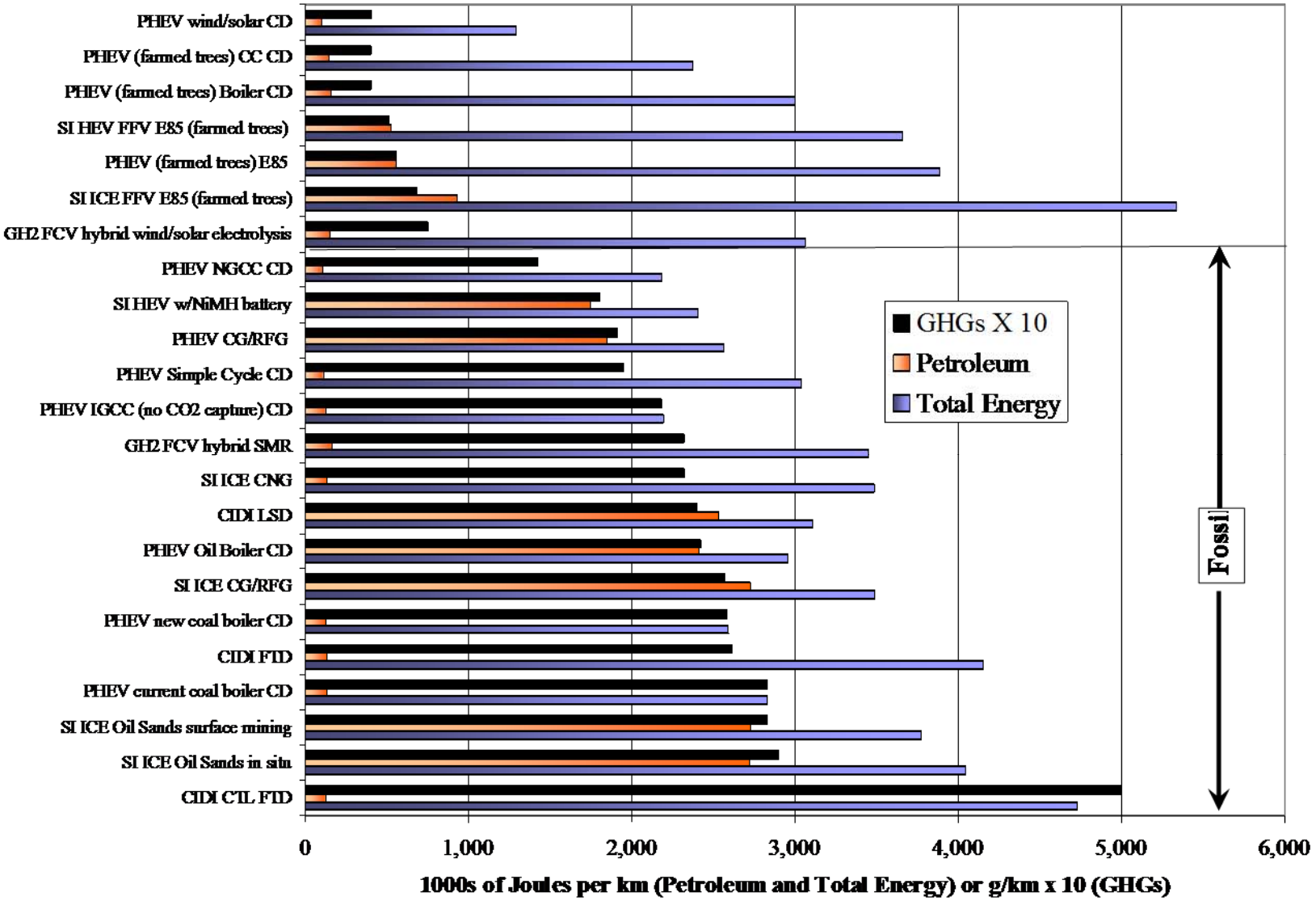
According to the Only MIT Simulation Test, a 35% Reduction in PHEV Power Causes a Drop of Fuel Saved of Only 10%



Key Potential PHEV Market Entry Barrier 3 – Assurance of Emissions and Air Quality Net Benefits

- Full-fuel-cycle power system criteria pollutants (EPRI analyses)
  - For PHEV operating all electrically in 2030, EPRI estimates:
    - *Primary particulates emissions increase (absent GHG policy)*
    - *Primary plus secondary particulates in air decrease! (no GHG policy)*
    - *Widespread, consistent, but small ozone reductions (no GHG policy)*
    - *With GHG policy the power plant mix will be cleaner*
    - *Power plant mix can be manipulated via smart charging (to manipulate either GHG or criteria pollutant results)*
- Air quality for PHEV operating in blended mode in 2015:
    - *Net air quality effects have not been studied*
    - *Emissions tests imply blended PHEV can have lower emissions than average light duty vehicles*
- Battery manufacturing increases sulfur oxides, decreases other pollutants
- GHG emissions reductions vs. conventional vehicles are assured
- GHG emissions vs. HEVs improve in most regions, even w/o policy

Barrier 3 – Initial Estimates of Life Cycle Emissions



Total energy, petroleum, and GHGs per kilometer driven [Gaines et al, 2007], various fuel paths

Barrier 3 – Estimation of Life Cycle "Criteria Pollutant" Emissions (Not Air Quality or Population Exposure!)

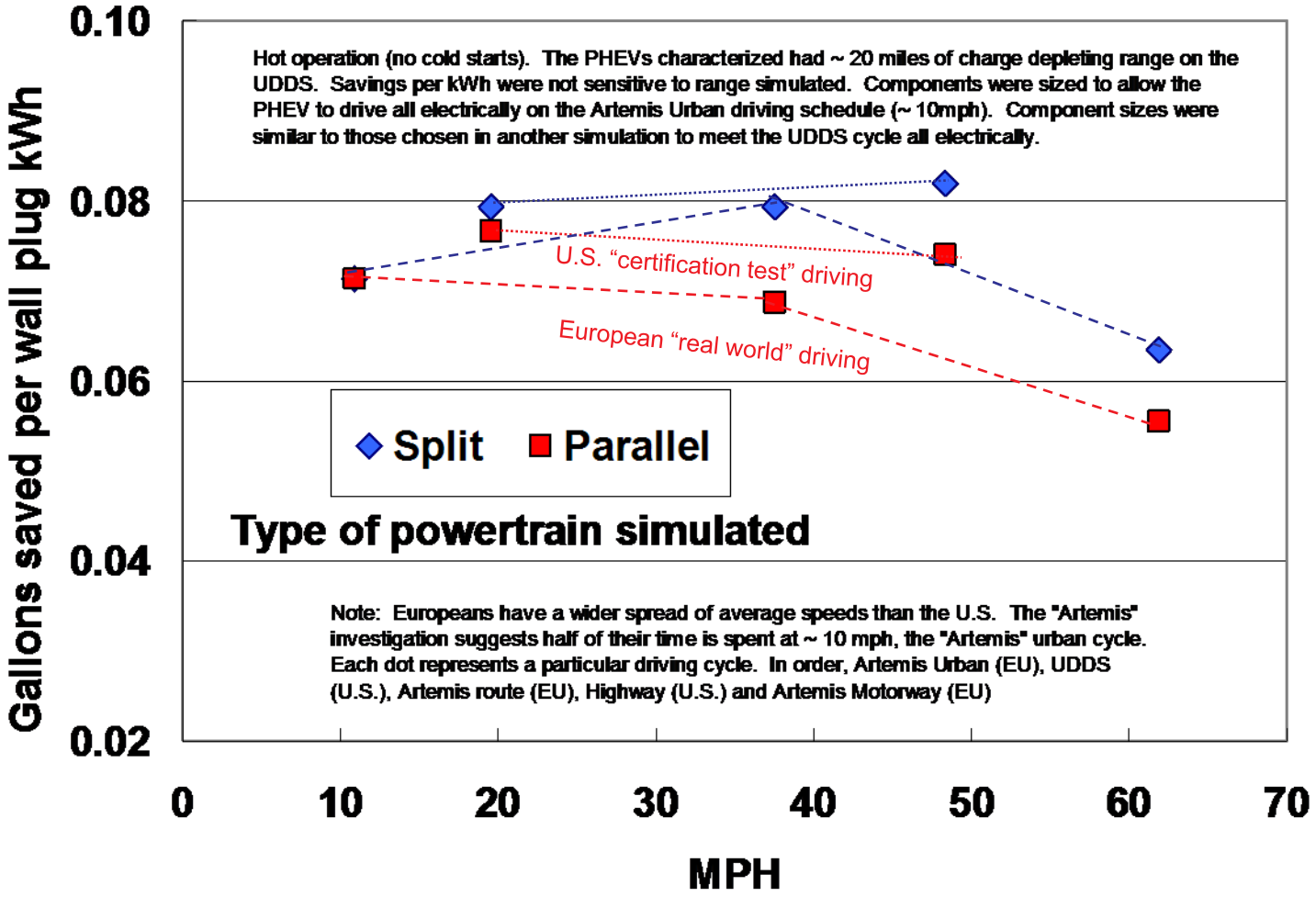
			Plug-in HEVs running all electrically in charge depleting (CD) mode						
	Petrol		Natural gas	Coal				Renewables	
	SI NA IDI	SI HEV w/NiMH Battery	Com-bined Cycle	New boiler	New boiler, zero powerplant NOx &SOx	IGCC	IGCC, zero powerplant NOx & SOx	Combined Cycle Farmed Trees	Wind Solar
CO	2.35	2.35	0.23	0.21	0.21	0.19	0.14	0.19	0.17
VOC	0.29	0.24	0.14	0.15	0.15	0.14	0.19	0.13	0.13
NO_x	0.20	0.16	0.12	***0.27***	0.08	0.15	0.08	0.10	0.06
$PM_{2.5}$	.036	.035	.034	***0.11***	***0.11***	***0.10***	***0.10***	.032	.025
SO_x	0.14	***0.19***	***0.20***	***0.69***	***0.20***	***0.27***	***0.20***	***0.26***	***0.19***

Life cycle emissions vs. base petrol, 7 charge depleting options

Note: Bold italics indicates higher pathway emissions than base conventional vehicle. SOx increases due to battery manufacture

- **Performance** –
  - emphasize fuel savings per kWh of electricity use as effectiveness metric

PSAT Simulations Imply a Loss of Charge Depletion Mode Effectiveness on EU Motorways and U.S. Rural Interstates; Consistent Effectiveness in Metro Area Driving. CARB Rated PHEVs May Allow More CDE in Europe than U.S.



One FY 2008 Question – Could ~ Same Cell & Pack Module Configurations Meet Multiple Objectives?

- PHEV10-20 often in blended mode with relatively low total pack power
  - (PHEV option along with HEV, often with conventional powertrains)
- PHEV30-40 all-electric capable in congested urban commutes, but blended in high speed free flow on Interstates
  - (Dedicated PHEVs with new vehicle bodies, no HEV option)
- City EV with 60-80 miles of range, capable of Interstate free flow
  - (Dedicated EVs with new vehicle bodies, no PHEV option?)

Plans for FY 2008

- Begin detailed evaluation of recycling and/or reuse of batteries
- Improve and detail methodology of estimating fuel savings
  - *Define differences for charge depleting & charge sustaining driving*
  - *Examine alternate fuel savings metrics – per mile, per hour, per kWh*
  - *Prepare initial dual mode powertrain simulations*
- Verify early "one-off" findings to determine whether generic
- Refine and expand market penetration investigations
  - *Engineering economics – how can government and consumers get most fuel savings per $?*
  - *Consumer preferences – will consumers purchase PHEVs for reasons other than fuel savings alone ?*
- Give papers and presentations on key study topics and findings
- Complete comprehensive study of PHEVs, City EVs with EPRI