Clean Cities

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# Highway Vehicle Electric Drive in the United States: Current Status and Issues


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# *Petroleum, Emission, and Carbon Benefits*

- **Electric generation uses almost no oil (1.2%, 2008)**
- **PHEVs can be designed to meet or exceed strict tailpipe emissions standards, being similar to, or better than already clean HEVs.**
- **Even if coal power were to remain dominant (doubtful), net air quality effects of "Volt-like" PHEVs would be positive (EPRI)**
- **Electric miles will reduce GHGs. Benefits become dramatic as % of gas in fossil generation dominates & with significant renewables.**
- **Implementation of electric drive and wind power has strong positive synergism.**
- **Electric drive offers well-to-wheel pathways with the most miles per unit of raw energy supply, for all alternative sources examined, maximizing resource sustainability.**

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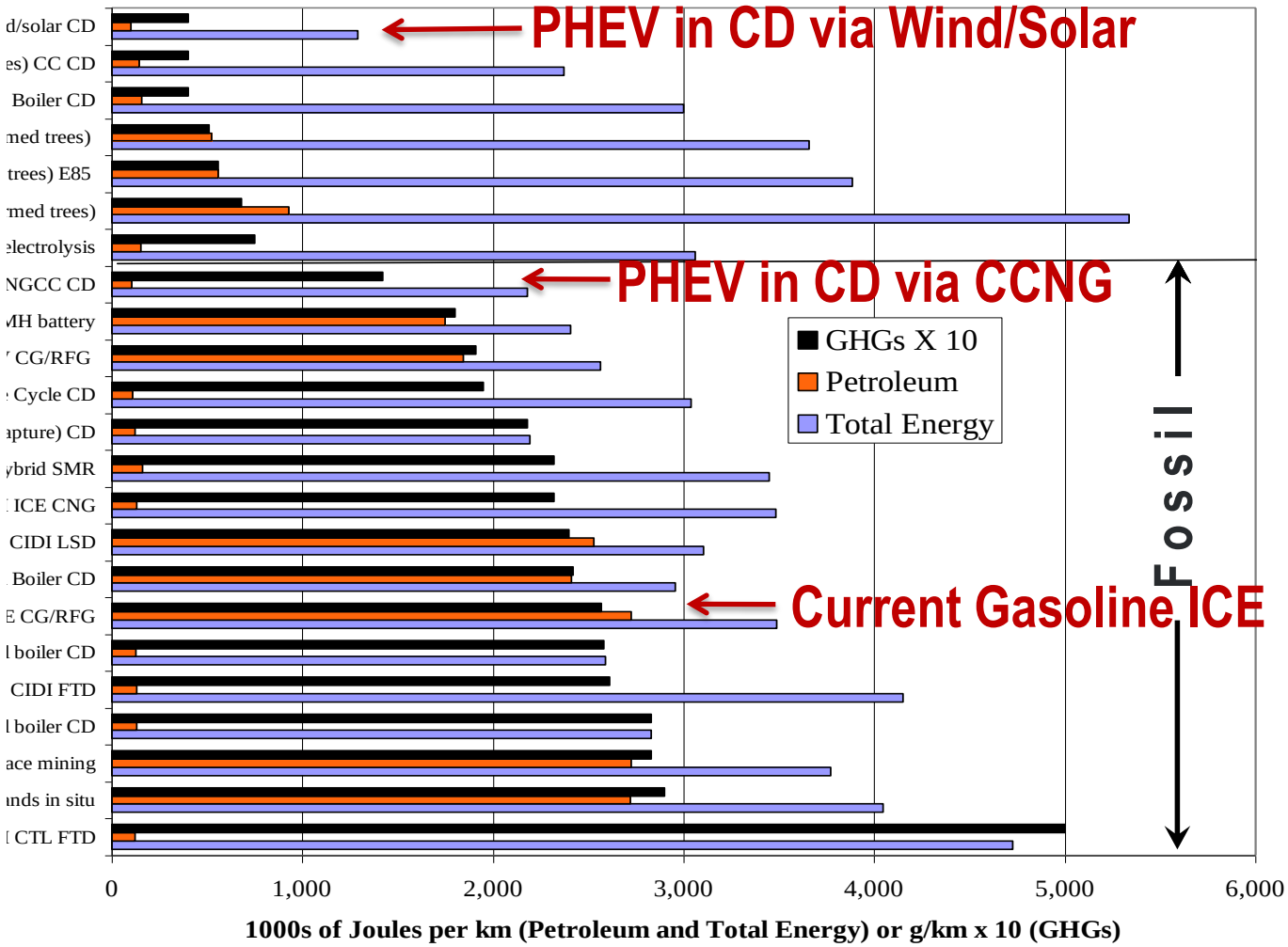
# *Of Many Options, a PHEV in CD Via Natural Gas Combined Cycle Power is "Best Fossil". Wind/Solar is Best Renewable*




 Gaines et al: Sorting Through the Many Total Energy Cycle Pathways Possible with Early Plug-in Hybrids . World Electric Vehicle Journal, Sept. 08, pp. 1-23

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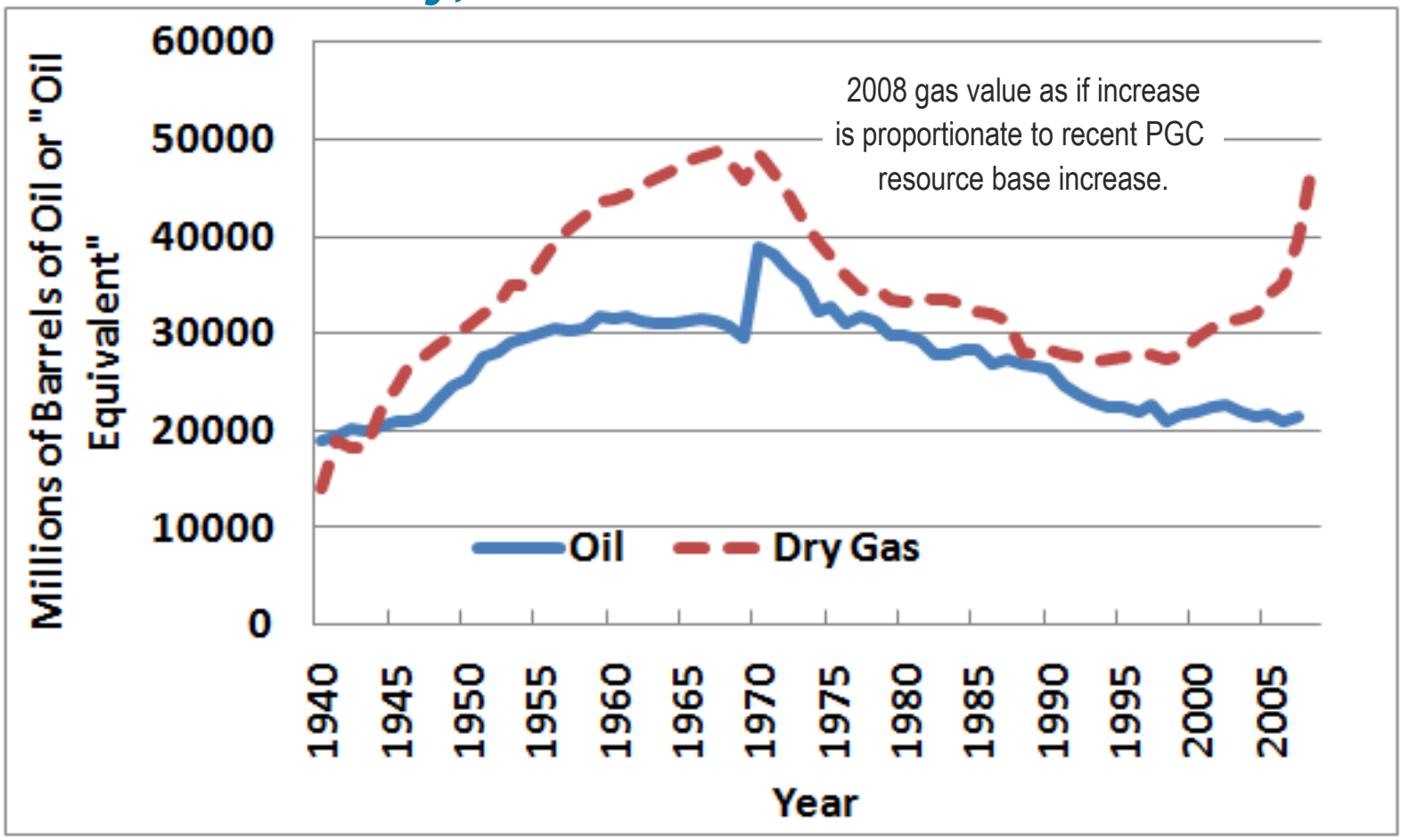
# *Estimates of U.S. Gas Reserves Have Gone Up Recently, as Oil Reserves Declined*



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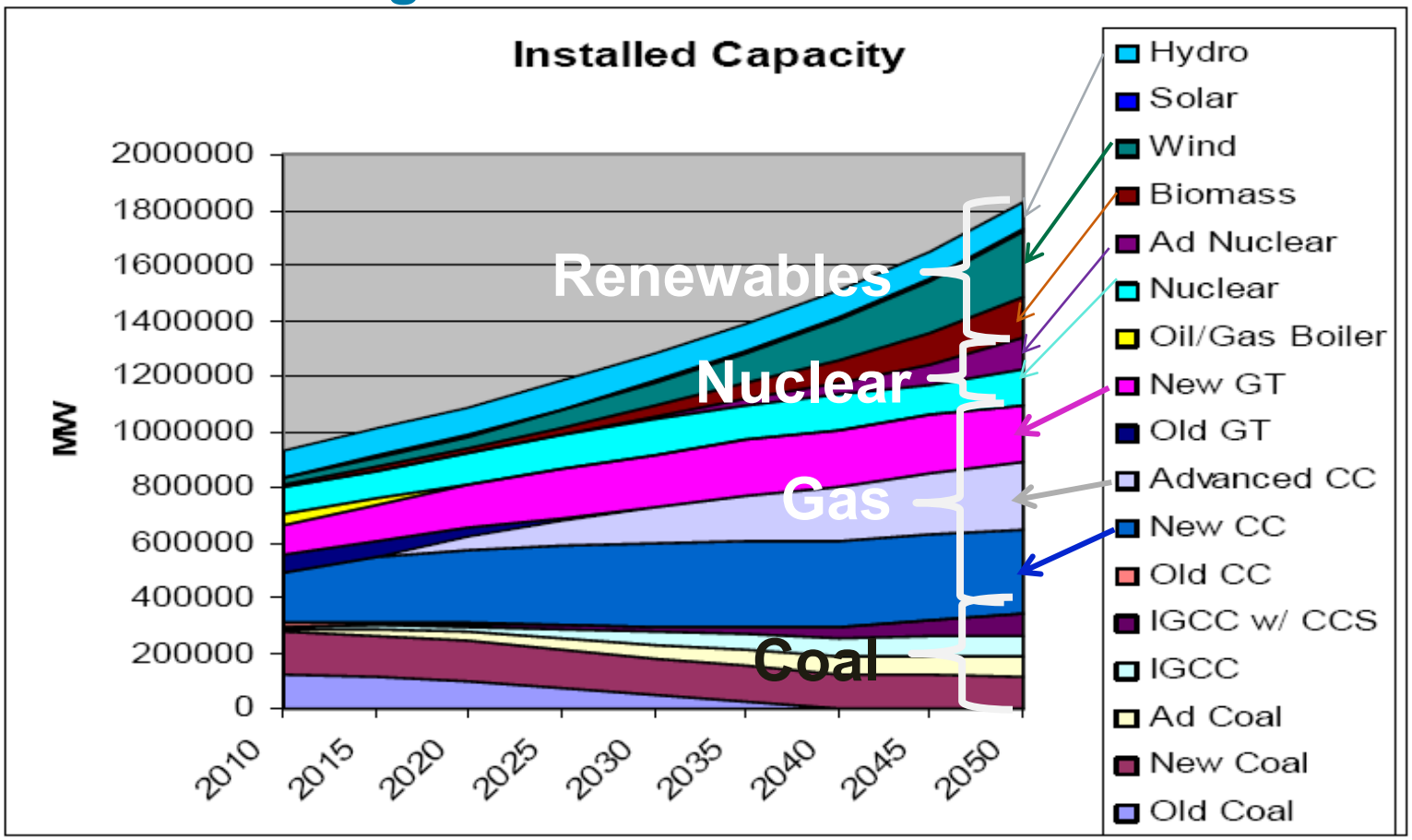
# *Before Recent Natural Gas Discoveries, EPRI Projected New Gas Generating Units To Dominate W Carbon Limits*




**Predicted changes in U.S. generation capacity, carbon constrained case [Knipping and Duvall, 2007] (courtesy of C. Clarke and Electric Power Research Institute)**

# Vehicle Acronyms

*ICE = internal combustion engine*

***<u>Powertrains below have an ICE and 1 or 2 electric machines</u>***

*HEV = hybrid electric vehicle*

*GCRHEV = grid connectable retrofitted HEV(new, low E-kW)*

*GCHEV = grid connectable hybrid vehicle (new, for low E-kW)*

*PHEV = plug-in hybrid*

*E-REV = GM's preferred term for the Volt*

# PHEV operating/control strategies

*CD = charge deplete using 50-70% of the battery state-of-charge (SOC)*

- *All-electric requires battery and motor to have > 90 kW (Volt)*
- *Blending occurs when battery & motor power is low*
  - *GCRHEV ~ < 20 kW (A123 Hymotion Prius)*
  - *GCHEV ~ 25-40 kW (Prius and Escape PHEVs in testing)*
  - *PHEV 40+ kW (likely OEM upgrades at commercialization)*

*PHEVXX = XX indicates charge depleting range (which really varies)*

*CS = charge sustaining – HEV operation, but at lower SOC for plug ins*

# *Electric Drive Is Being Implemented in Many Ways*

**No plug, no grid electric energy**

**HEV** = hybrid electric vehicle

Electrified Vehicles

**With existing & new plugs, both grid energy & gasoline**

**GC**(R)**HEV**

**PHEV** = plug-in hybrid

**E-REV** = extended range electric vehicle

**New plugs, charging stations**

**No gasoline, only electricity**

**EV** = electric vehicle

# *Current hybrid types, terminology set one*

## Available Cars and SUVs

Parallel (Honda IMA, GM mid-size car “BAS” HEVs)

Split (Toyota Prius etc., Ford Fusion & Escape, Nissan Altima)
(dominant in the HEV market today,
mostly parallel, a little series)

GM Dual (or Two) Mode (3 Large SUVs, 4 Door Pickup Truck)

## Medium Duty Trucks

Pre-transmission
(experimental “Sprinter” truck, Eaton trucks)

## Coming Car (E-REV, not HEV)

Series (EV - how the Volt will run when charge depleting)

# *Current hybrid types, terminology set two*

## One electric machine systems (less cost, less function)

**Stop-start** (Mini in Europe)
**Micro** (BMW in Europe)
**Mild** (Honda, GM BAS in U.S.)

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**Full or strong** (Daimler Sprinter, Eaton Trucks)

## Two electric machine systems

**Full or Strong** (different words, same meaning)
(Toyota, Ford, GM Dual-Mode [or 2-Mode])
**Extended range electric vehicle (E-REV)**
(GM Volt, possibly others – "very strong?")

Plug-ins

Adequate power is probably a distinguishing factor for logical OEM development of a PHEV type from an HEV.

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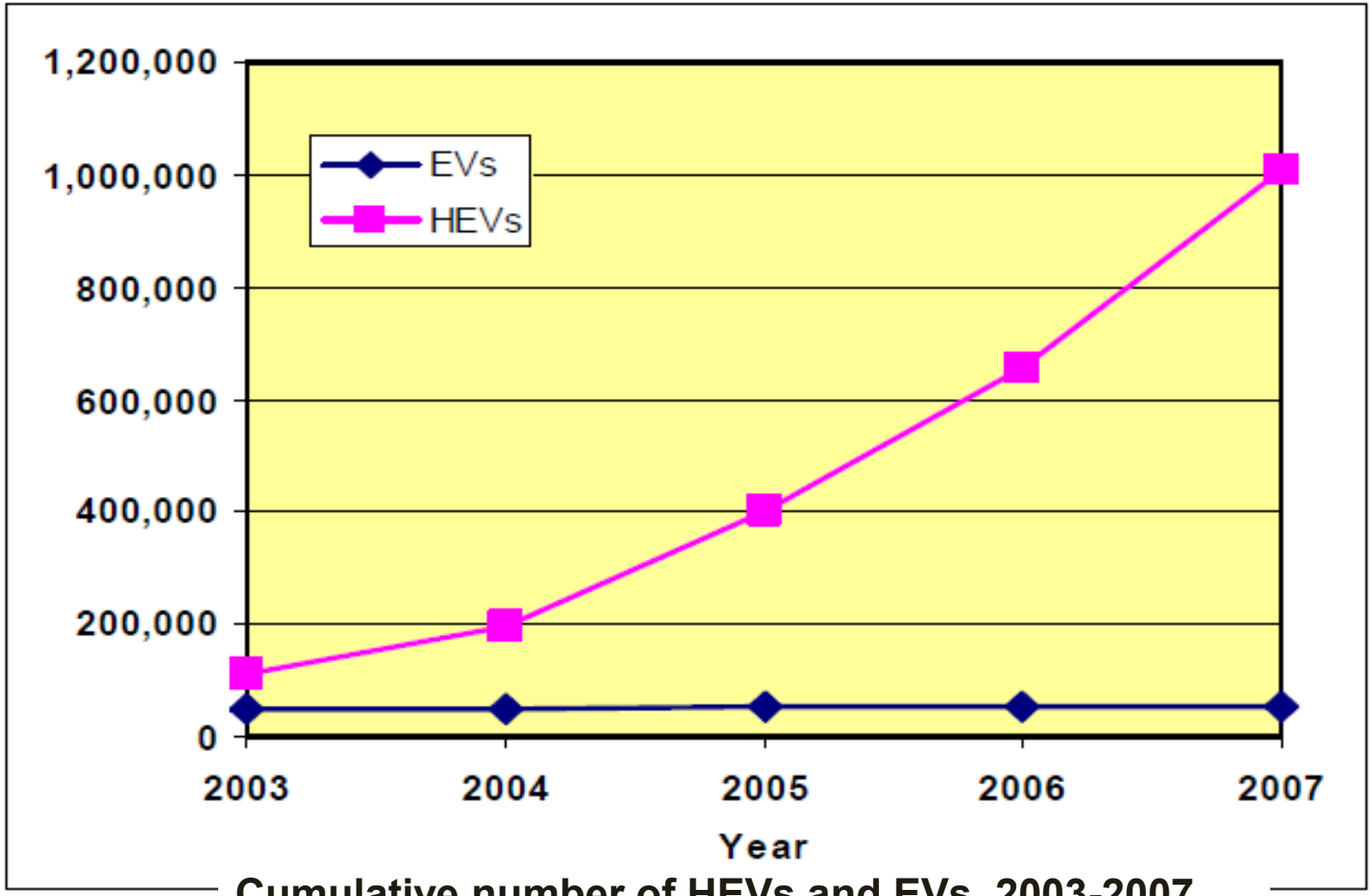
# *The HEV is the Reason For Success of Electric Drive to Date*




**Cumulative number of HEVs and EVs, 2003-2007**

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# *If Slow Overnight Charging from a Standard Wall Outlet is OK, Electricity Provides Far More Refueling Stations than Any Fuel*

**Level One**

- 1.1 kW, 15 amp, 110 V
  - Restricted to at home only, overnight full charge
  - 9 pm to 9 am, randomized start, full plug-in HEV charge

**Level Two**

- 3.3 kW, 15 amp, 220 V
  - Restricted to home and work
  - Charge at any time, charge until full
  - Effectively two plug-in HEV charges per day

**Level Two Plus?**

- 6.6 kW, 30 amp, 220V
  - Unrestricted location; wherever you park
  - Charge anytime; charge until full
  - Several plug-in HEV charges per day

**Level Three**

- 50 kW, 100 amp, ~400V
  - Refueling station concept for EVs
  - Charge anytime; charge until full
  - Up to hundreds of charges per day

# *Costs for Charging Circuits Increase with Charging Level and for Retrofit vs. New*

- Level 1 Residential
  - $0 = 15 amp standard household plug
  - $200 15 up to 20 amp (circuit & outlet near electrical panel) (EPRI 2002)
  - $830 (Apt., 20 amp) $880 (House, 20 amp) (Morrow, et al, 2007)
- Level 2 Residential (per space when apartments)
  - $1000 40 amp (circuit & outlet near electrical panel) (EPRI 2002)
  - $700-2300 (Carolin, Nissan, 2009)
  - $1520 (Apt.) -$2150 (House) (Morrow et al, 2007)
  - Retrofit - $4000 (Boyce, Plug-in 2009, A. Vyas ANL notes)
  - City of Vancouver - $500-1500 for new apartment complexes

  Commercial $1850 (Morrow et al, 2007)

  Boyce SMUD (Commercial retrofit @ $6300, level not specified)
- Level 3 (to be found – tens of thousands?)

# *Circuit Upgrades Provide A More Capable Socket. Cord and/or Charger Upgrades May be Optional*

- Morrow, Karner and Francfort („07) estimated costs of the EVSE (Electrical Vehicle Supply Equipment) cord (connector?) within costs on prior slide.
  - Level 1 = $250
  - Level 2 = $200
- Tesla currently lists charging connectors as options
  - Level 1 = $600
  - Level 2 = $1500
  - Level 3 = $3000
- Moawad et al use $800 for an on-board charger, presumed to be at least Level 2 capable

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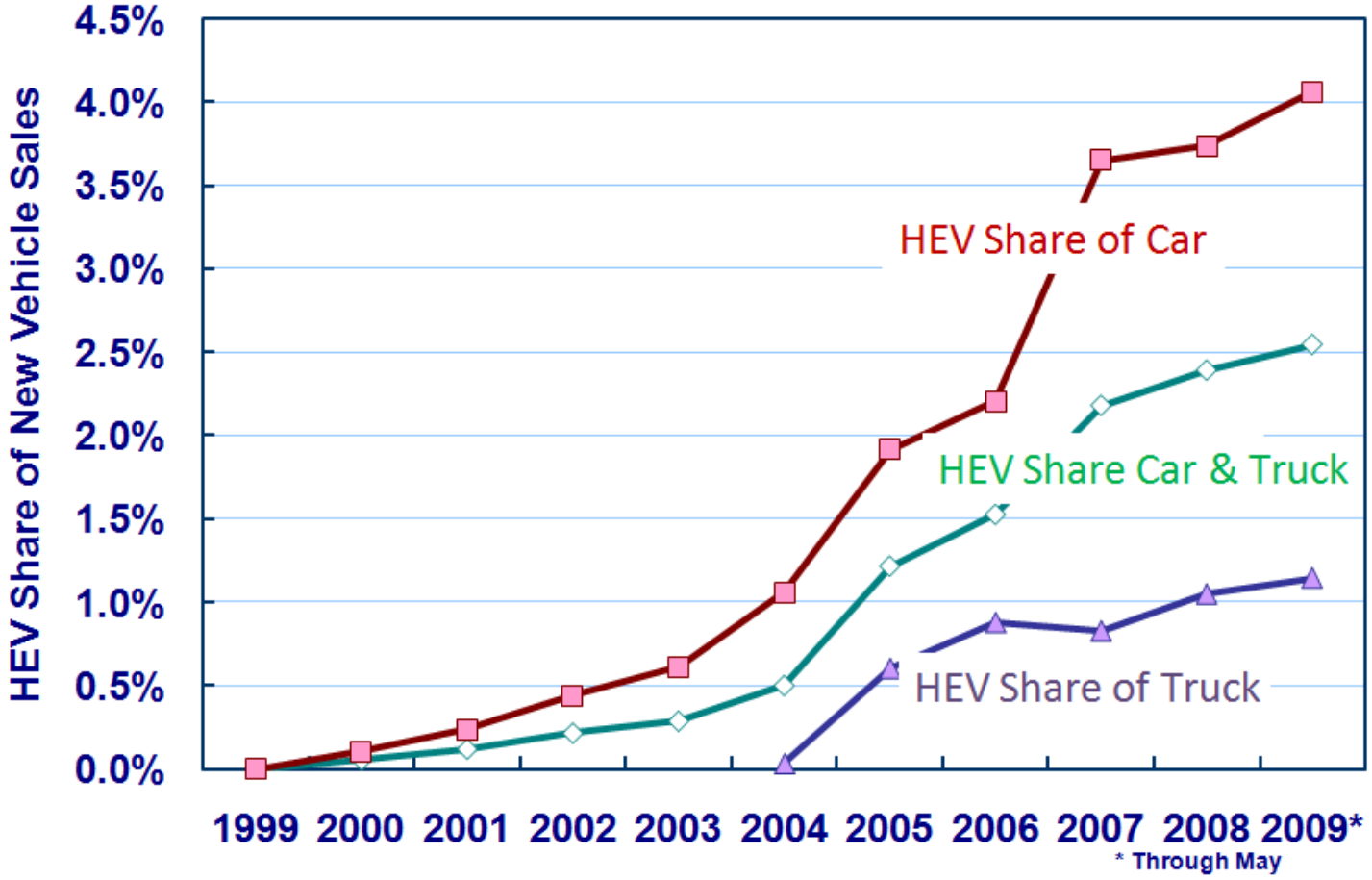
# *The Share of HEV Powertrains That Are in Cars is Far Higher Than the Conventional Vehicle Car Share*




**HEV Share of New Light Duty Vehicle Powertrains**

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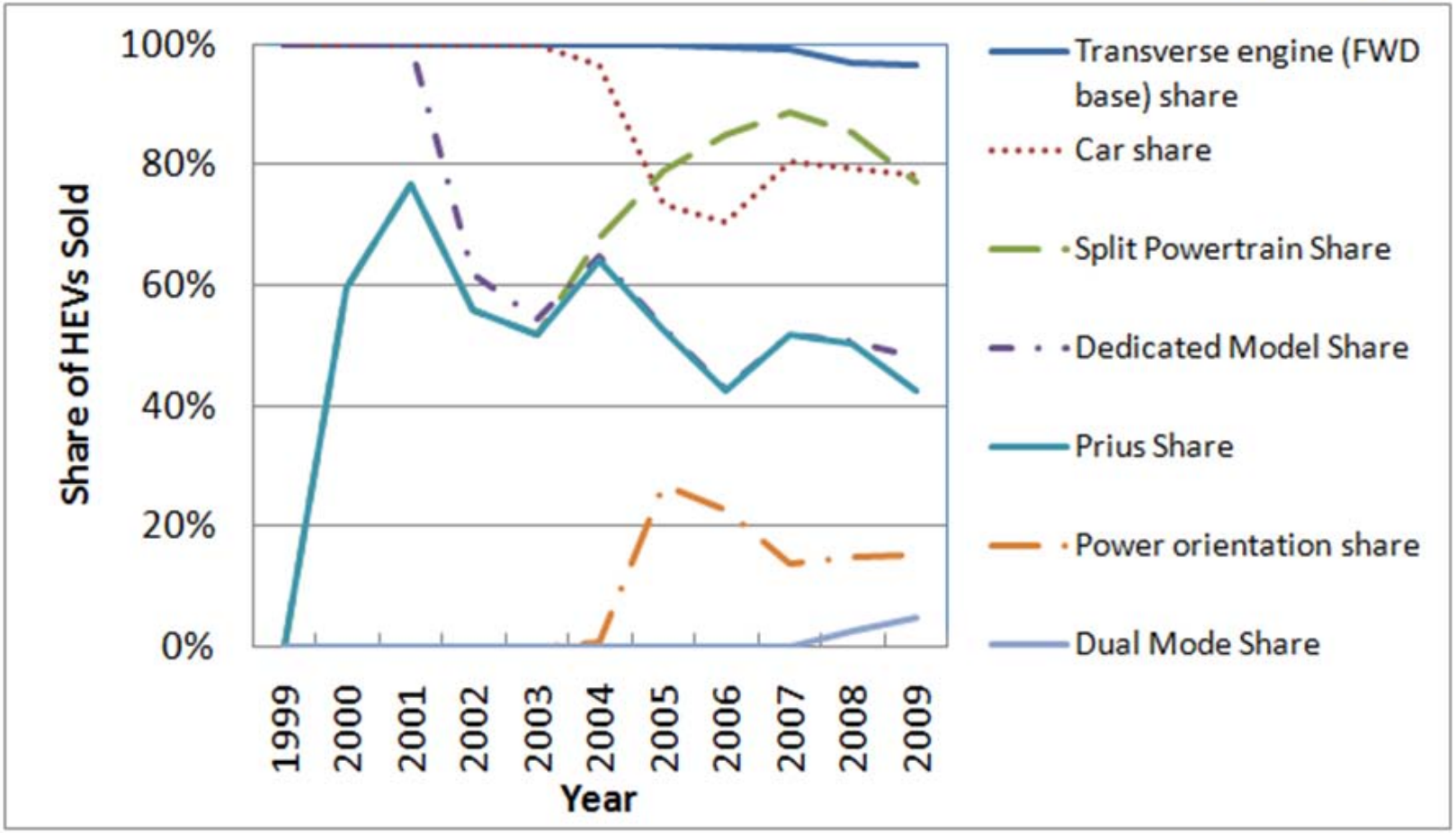
## *In HEV Market Share Terms, Introductions of Truck HEVs and Power Oriented HEVs Led to Peaks Followed by Drops*




Share of total hybrid powertrain sales, by category

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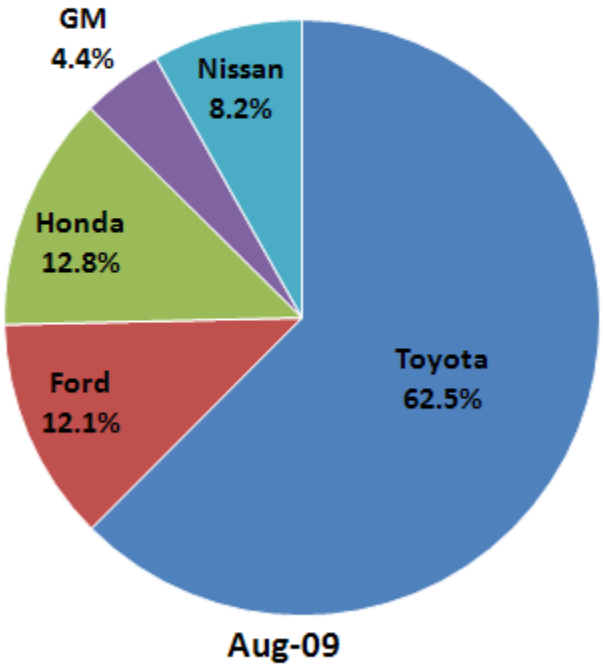
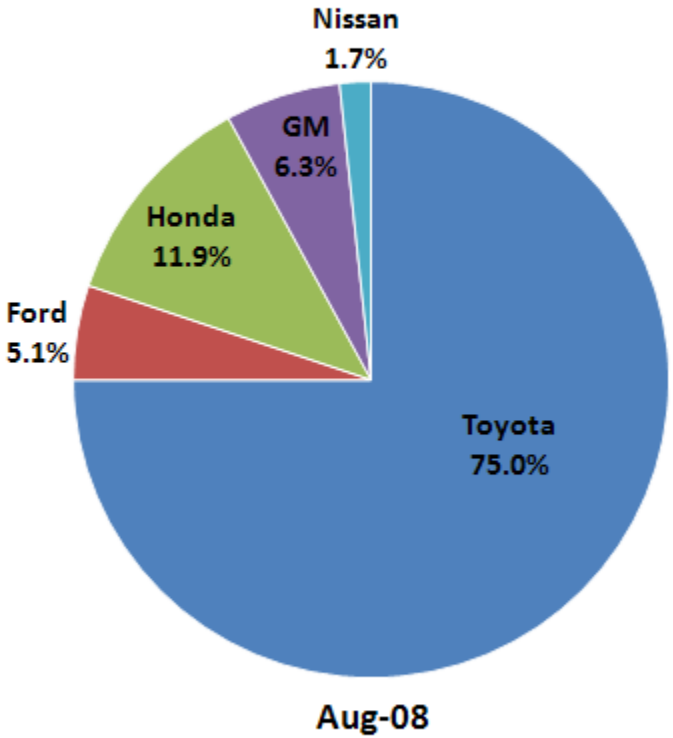
## *The Hybrid Market is Expanding, Has More Products from More OEMs, Creating Competition for Toyota*




Source: http://www.greencarcongress.com/2009/09/hybrid-sales-20090902.html

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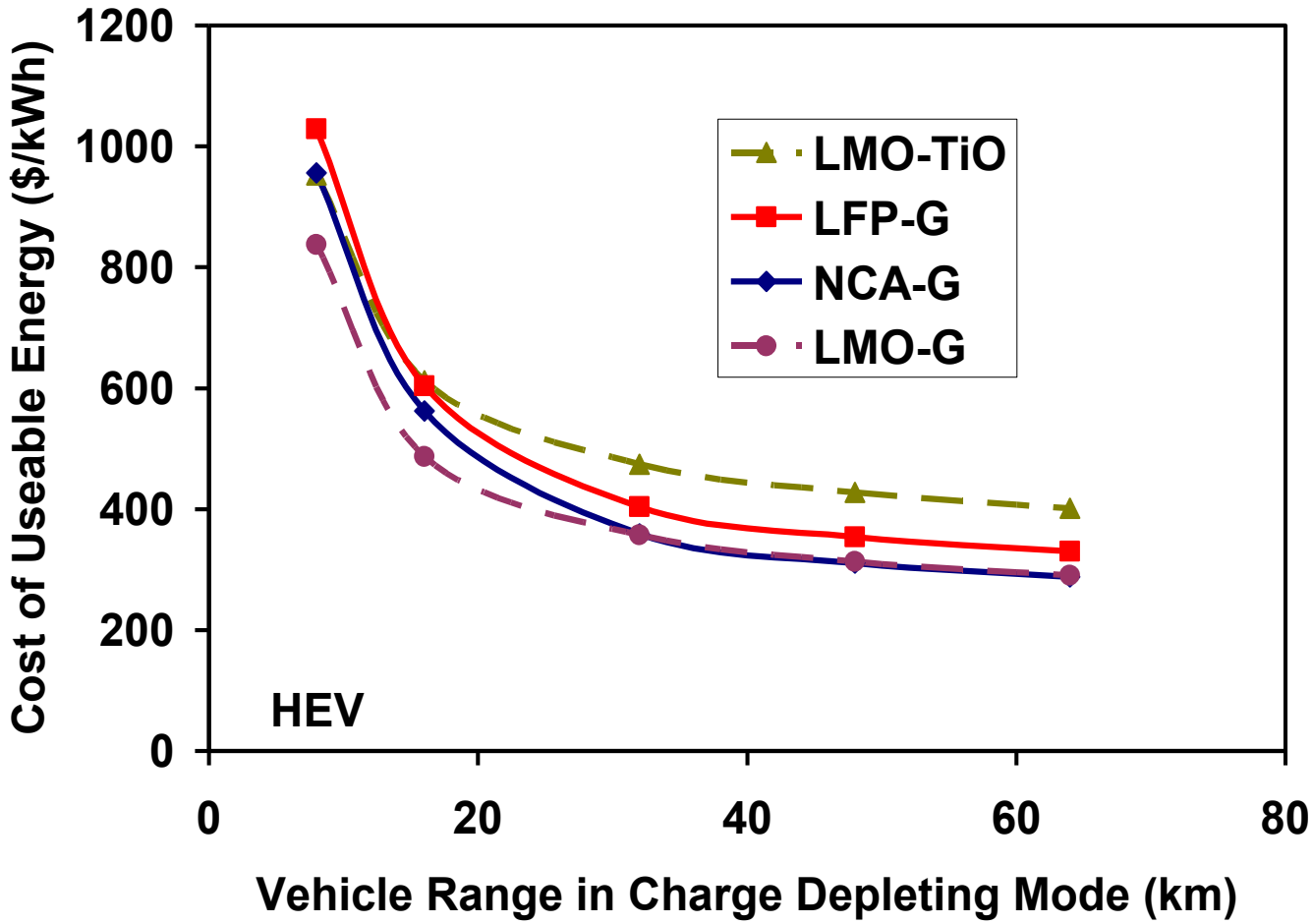
# *Pack W/Wh Drops for PHEVs vs. HEVs Mean $/kWh Initially Drops Sharply With CD Range For Leading Li-ion Chemistries*




Source: Nelson, Santini and Barnes, Presentation for: *Factors Determining the Manufacturing Costs of Lithium-Ion Batteries for PHEVs, EVS24; Stavanger, Norway, May 13-16, 2009*

# *The Cost of Making a PHEV From a Full HEV is < Cost of the HEV Over the CV (to ~ 15 mi. of CD Distance)*

| Powertrain Type (mid-size passenger car) | Total Vehicle Cost ($) | Increment in Cost from Prior Configuration ($) |
|---|---|---|
| Conventional | 17245 | N/A |
| HEV | 20029 | 2784 |
| PHEV 4kWh (~ 10+ mi. CD blended) | 21881 | 1852 |
| PHEV 8kWh (~ 20+ mi. CD blended) | 23709 | 1828 |
| E-REV 12kWh (~ 30- mi. CD electric) | 27487 | 3778 |
| E-REV 16kWh (~ 40- mi. CD electric) | 29338 | 1851 |

**Low production volume costs of HEV, PHEVs, and E-REVs**

Moawad et al. *Impact of Real World Drive Cycles on PHEV Fuel Efficiency and Cost for Different Powertrain and Battery Characteristics,* EVS24, Stavanger, Norway, May 13-16, 2009

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# *Toyota, Far and Away the Highest Volume Battery Pack Producer (900k/yr), Lists its Camry HEV for a Lower Price Increment than Competitors*

| | 4 vs. 4 cylinder | 4 vs. 6 cylinder |
|---|---|---|
| | HEV has more power | HEV has less power |
| Honda Civic (parallel) | $2645 | 6 not available |
| Ford Fusion (split) | $3450 | $2645 |
| Toyota Camry (split) | $2295 | $735 |
| VW Jetta Diesel | $3175 | |
| Moawad et al split estimate | $2784 | |

Retail price increment estimates by D. Santini, adjusting for variation in options offered

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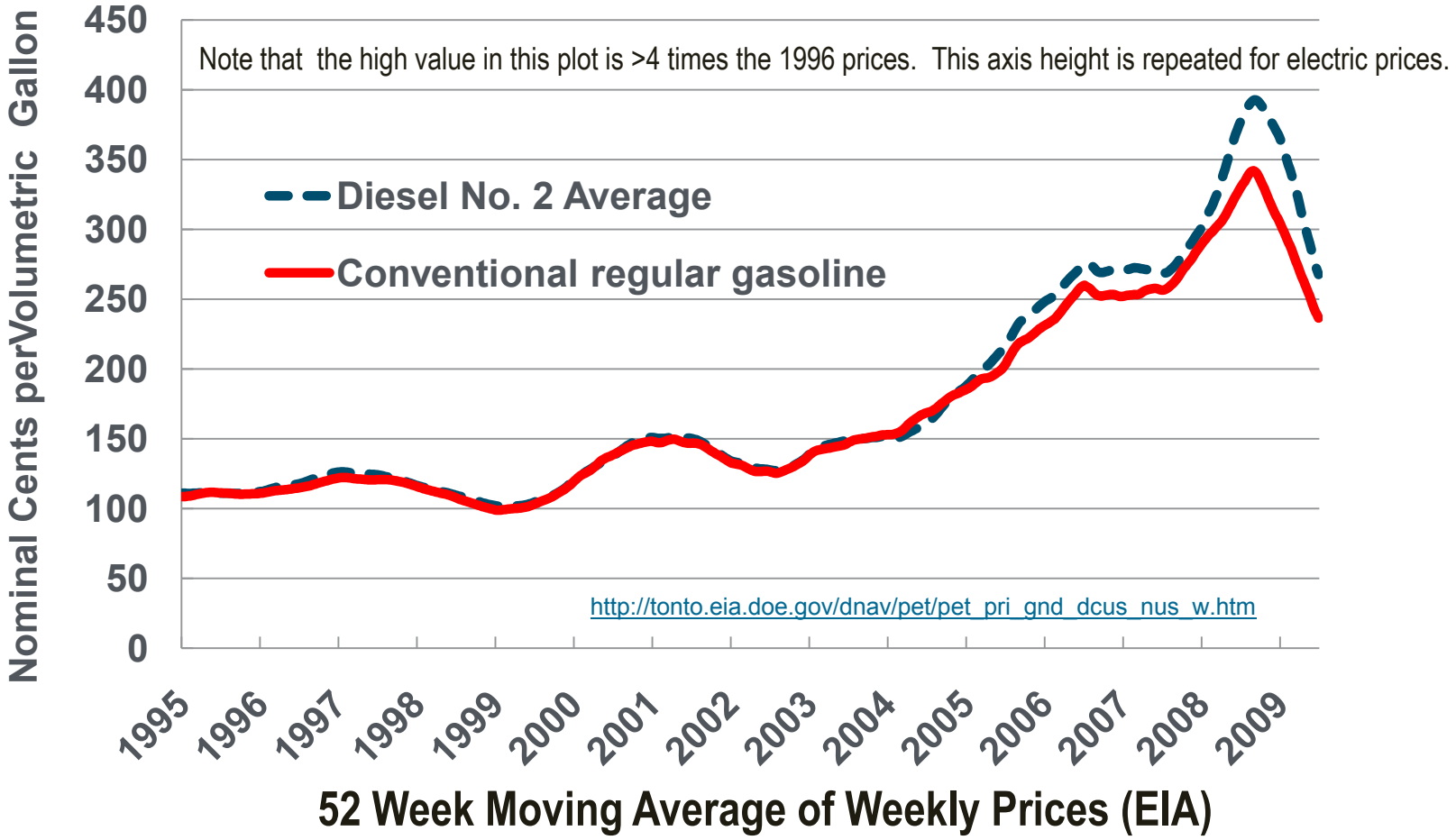
# *Since a 1990s Lull, Refined Products Prices Serving Conventional ICEs Revived Interest in AFVs and ATVs*



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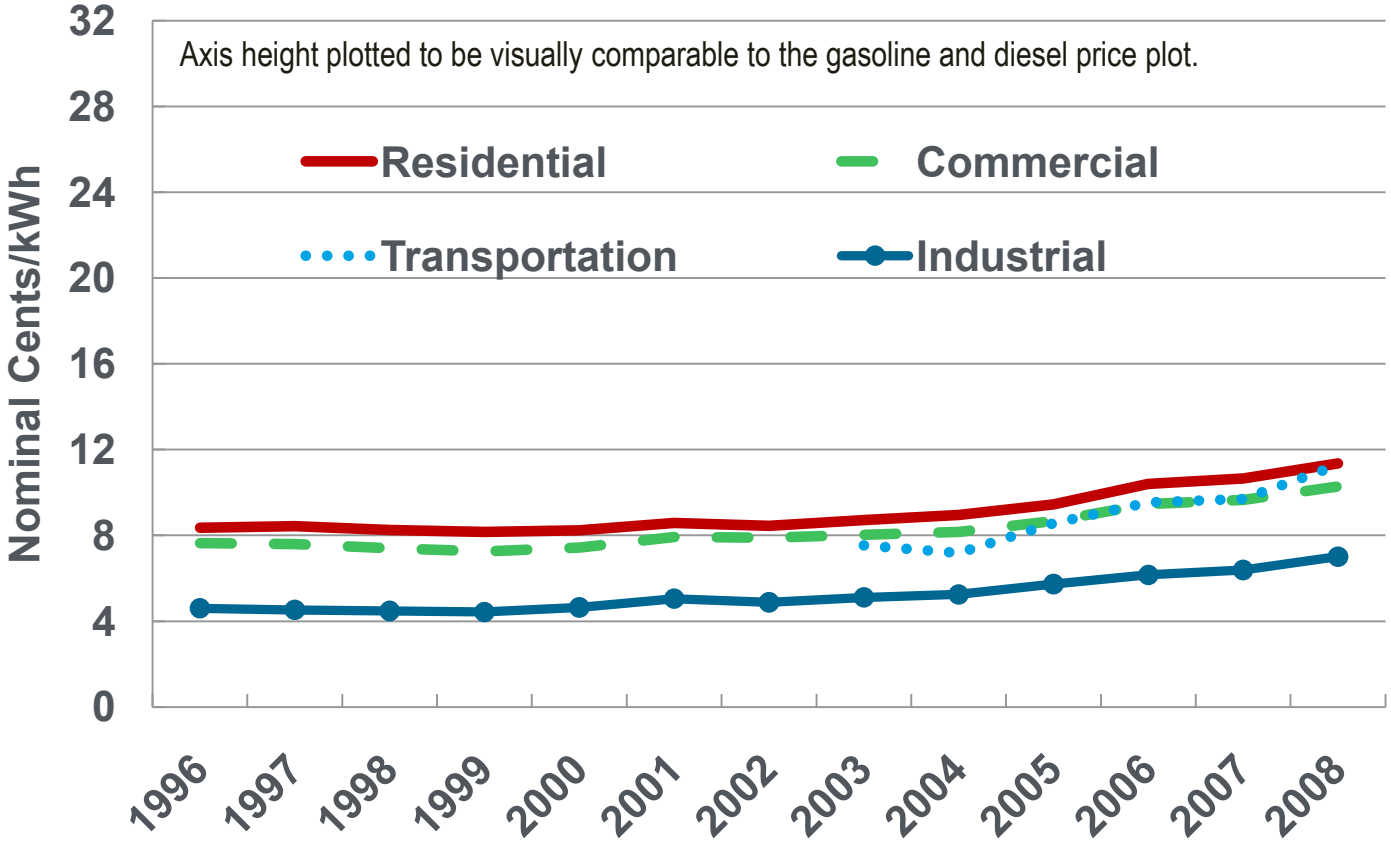
# *Compared to Gasoline and Diesel, Electricity Prices Were Stable From 1996, Making Electric Drive More Competitive*




**Annual Average Electricity Prices, 1996-2008 (EIA AER)**

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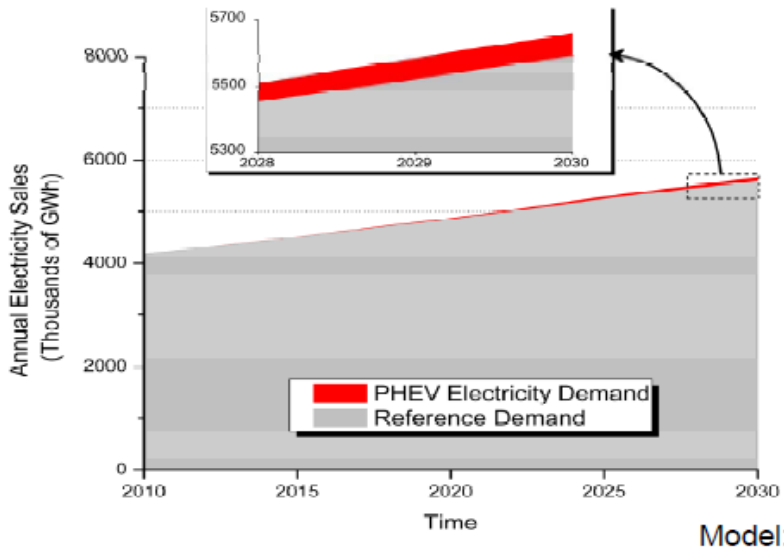
# *Studies Continue, and Local Details Vary and Must be Addressed, but the Aggregate U.S. Generating Capacity Can Handle Plausible Numbers of PHEVs for Many Years*

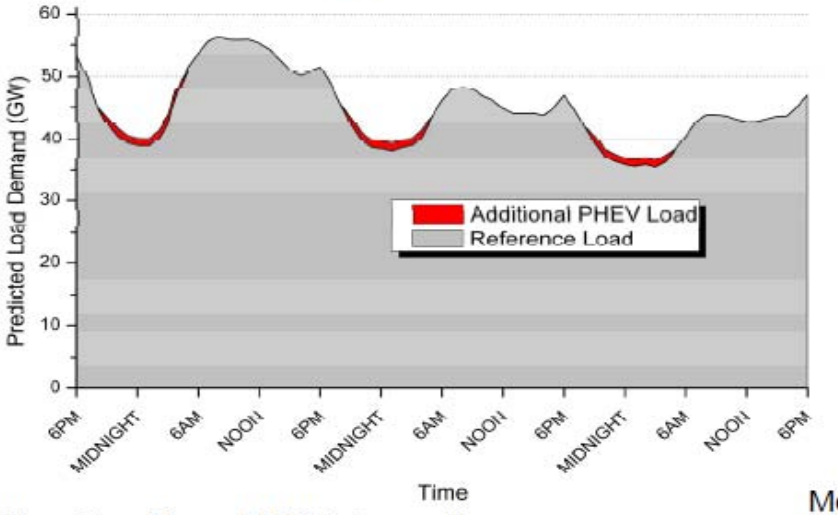
## U.S. Electricity Sales for PHEVs




Model: IPM

- Electricity sales from PHEVs represent a small fraction of total U.S. electricity demand (In 2030, 1.2% of demand is from PHEVs)

## PHEV Electricity Demand Likely in Off-Peak

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- Additional load from PHEVs is small
- PHEVs could be charged mostly via base-load filling during evenings and nights, when electricity costs are low

Source: Shelby and Mui, Plug in Hybrid Opportunities and Challenges, TRB presentation, 2007

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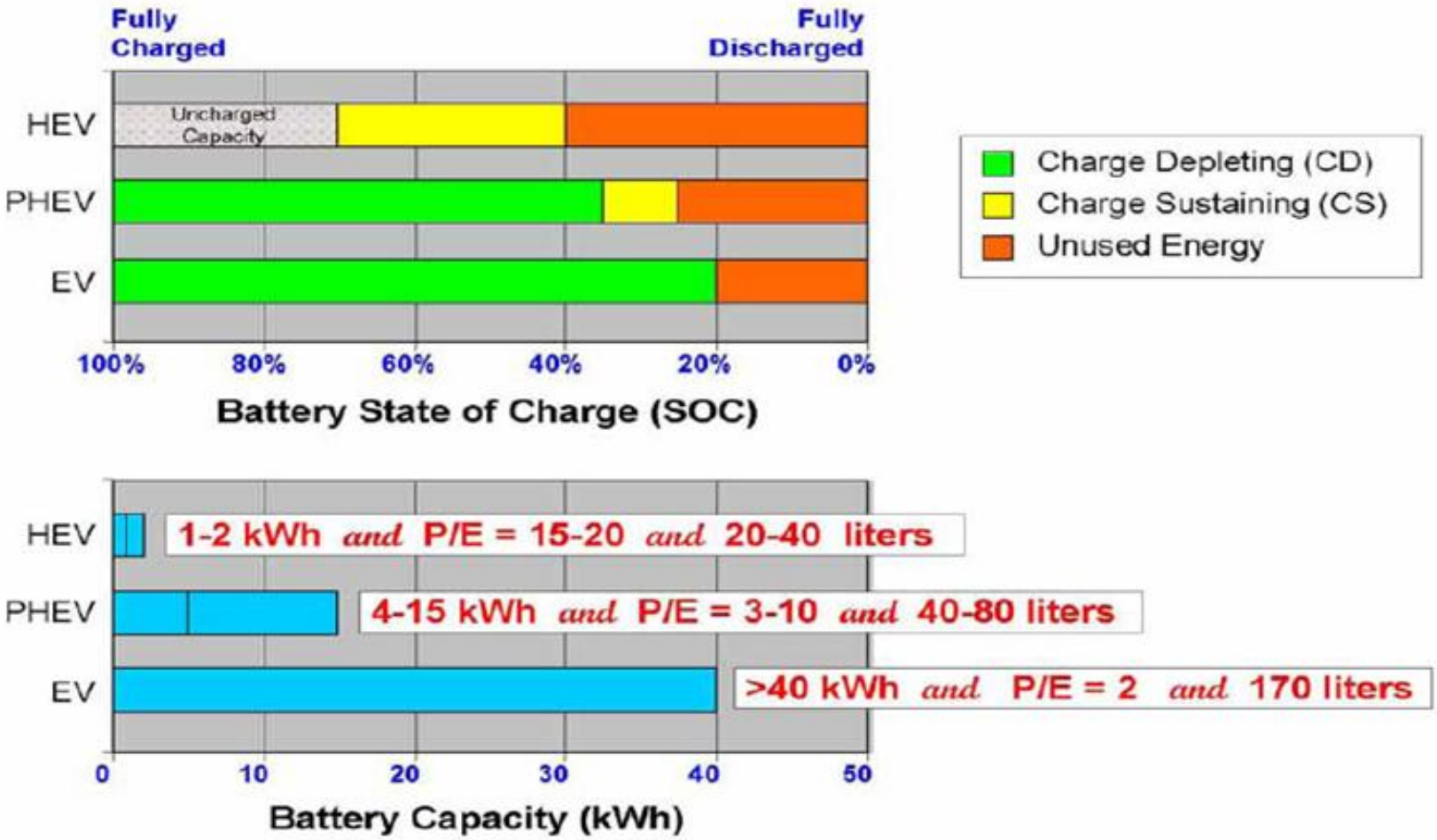
# *PHEVs Challenge Batteries More Than HEVs (due to a wide SOC swing) or EVs (due to consistent deep discharge)*



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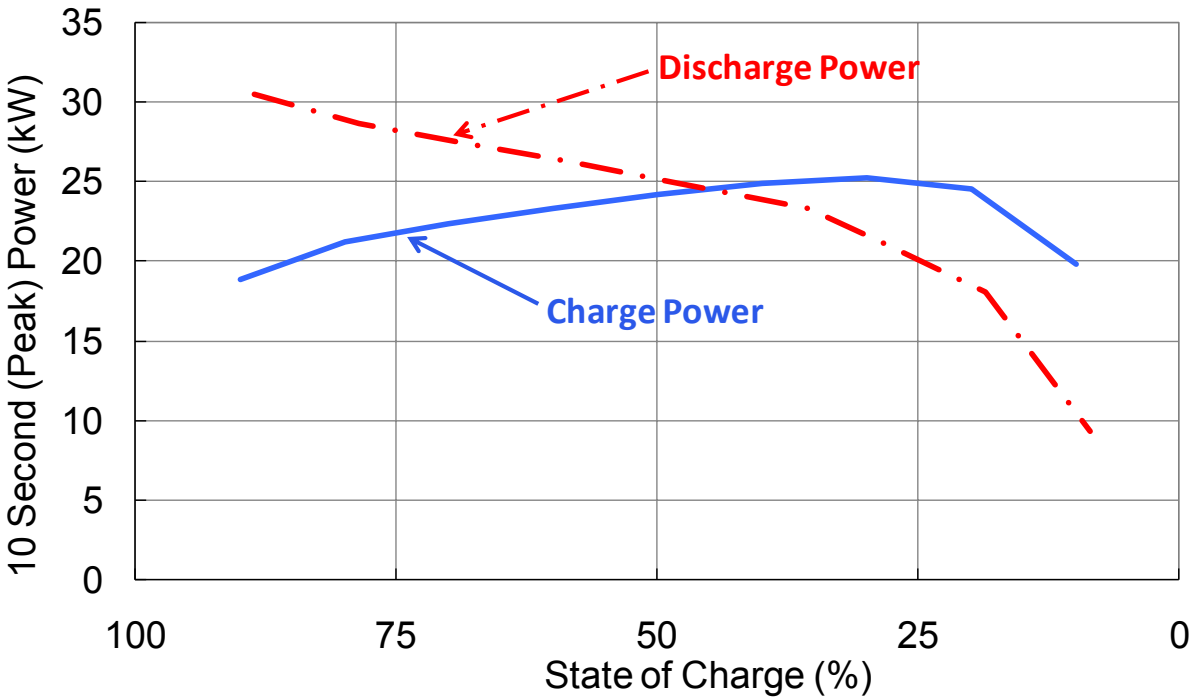
# *Battery Power Varies as a Function of State of Charge (SOC), is Different for Input and Output, Deters Battery Use at High and Low SOC Values, Fades With Use & Time*




Ten Second Input and Output Pulse Power vs. SOC, Ford Escape NiMH Pack

Source: Idaho National Laboratory PHEV Test

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# *Since a PHEV or EV replaces gasoline with electricity, MPG becomes a very poor measure of a vehicle's true efficiency*

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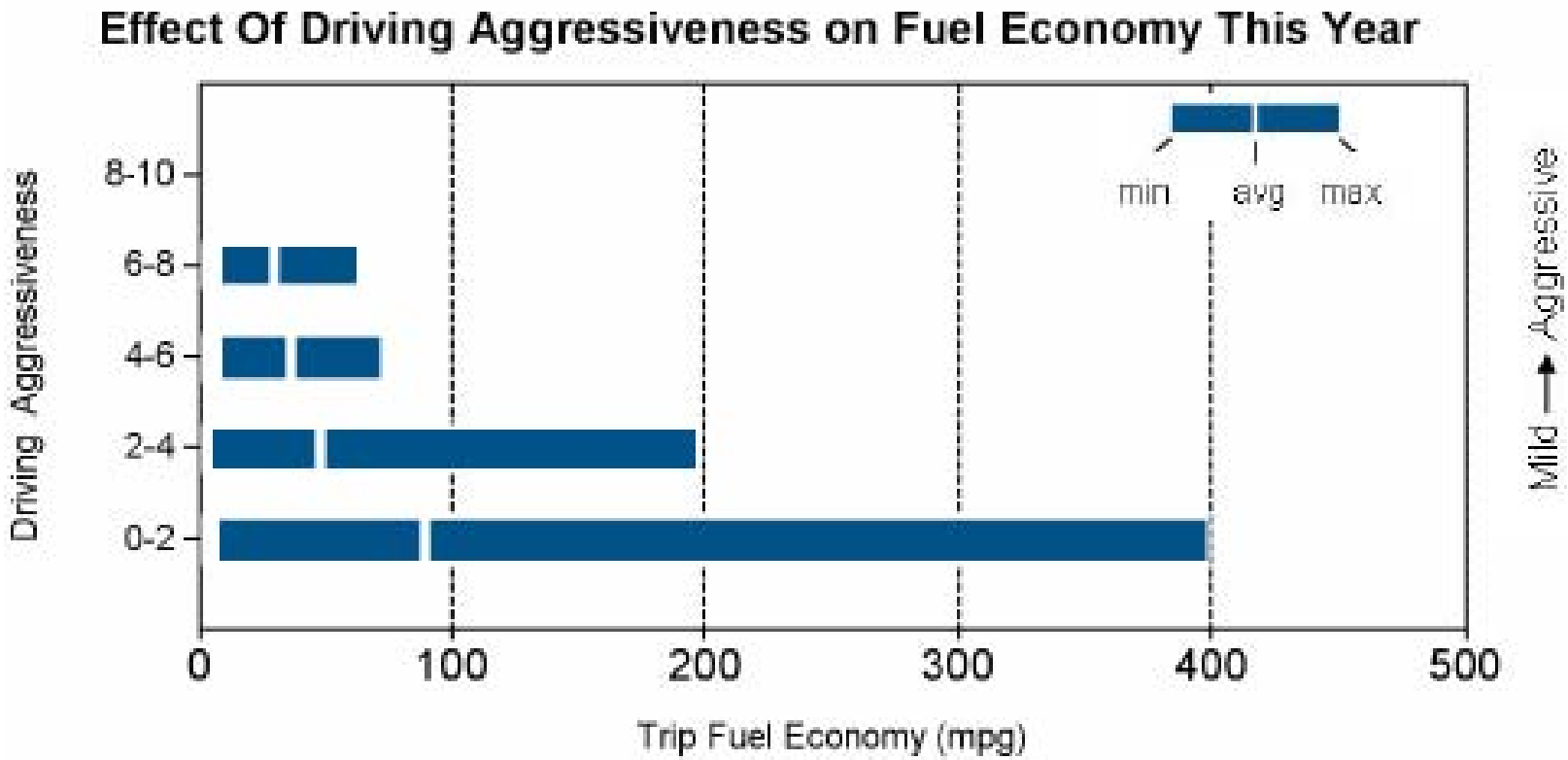
# *If You Buy a GCHEV (or PHEV) Instead of HEV Your MPG May Vary Sharply.*




Driving cycle aggressiveness is based on average accelerator pedal position
(From: North American PHEV Demonstration, Hymotion Prius [110 Vehicles])
(U.S. Department of Energy, EERE, OVT Website)

# *But CD Gallons Saved per Mile May be Fairly Stable*

| Type of test of Prius Hymotion GCRHEVs | CD Gallons per 100 miles | CS Gallons per 100 miles | CD Gallons saved per 100 miles vs. CS | Miles to depletion | Gallons saved per charge |
|---|---|---|---|---|---|
| Argonne UDDS dyno tests | 0.6 | 1.6 | 1.0 | 24.5 | 0.25 |
| Idaho NL "city" field tests | 1.6 | 2.6 | 1 | Unknown | Unknown |
| | | | | | |
| Argonne HWY dyno tests | 0.90 | 1.70 | 0.8 | 32 | 0.26 |
| Idaho NL “highway" field tests | 1.5 | 2.2 | 0.7 | Unknown | Unknown |

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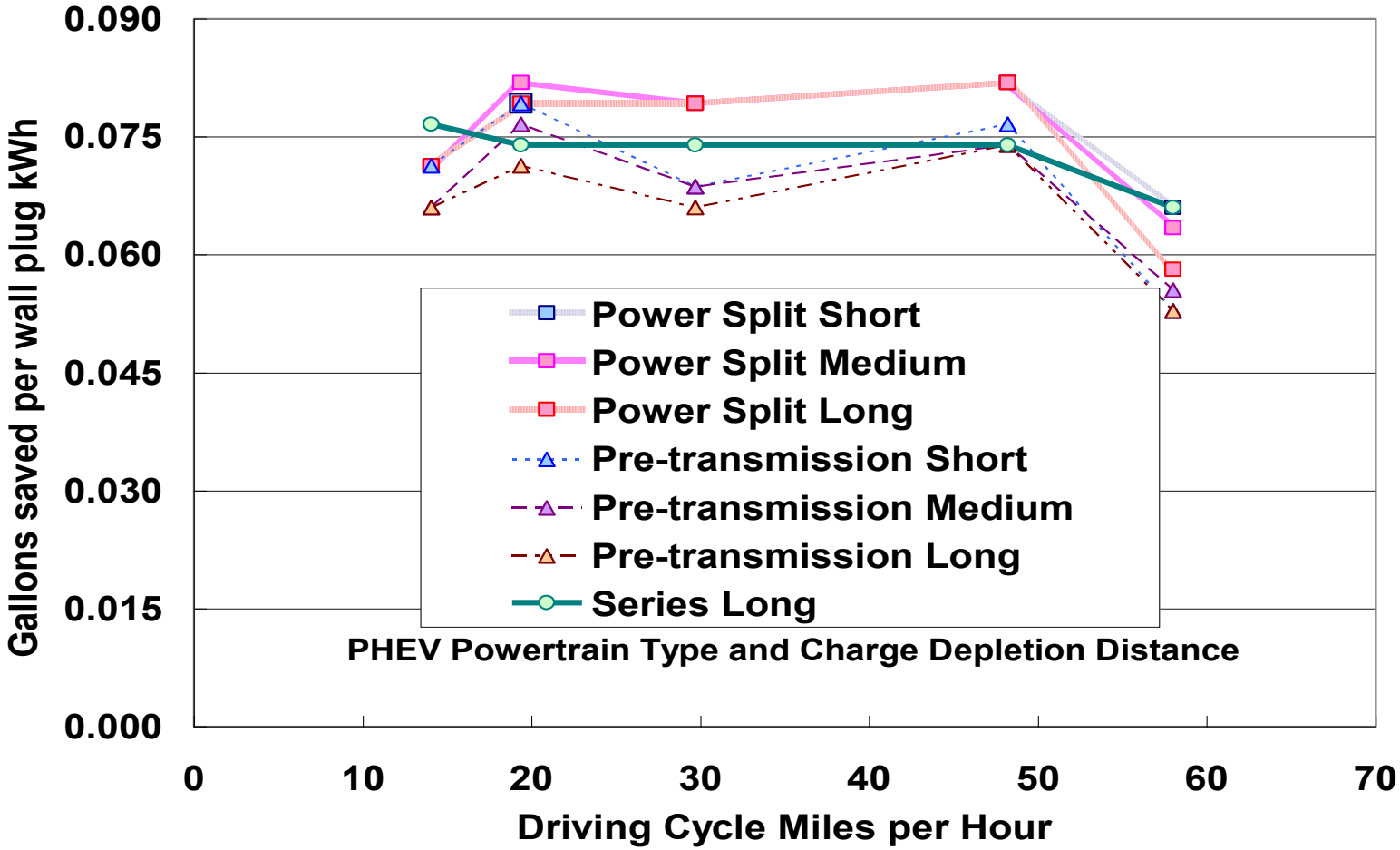
# And CD Gallons Saved per kWh Used More Stable




Santini and Vyas, "More Complications in Estimation of Oil Savings via Electrification of Light Duty Vehicles", Plug in 2008, San Jose CA

Passier et al, Status Overview of Hybrid and Electric Vehicle Technology . Report of the IEA HEV & EV Implementing Agreement, Dec. 2007

# *What Markets are Targeted for Electric Drive?*

**Current Niche Markets**

Prius retrofits by Hymotion
Tesla Roadsters

**Initial Target Markets by OEMs (a partial list, if other claims are believed)**

**Light Duty Vehicles up to 5 Adults occupancy (primary target)**

Prius –PHEV, perhaps GCHEV – mid-size car
Ford – unspecified PHEV, likely crossover SUV or mid-size car
GM – Volt 4 passenger E-REV – compact or mid-size car
Smart and Mini – 2 passenger EVs
Tesla – 5 (+2) Mid-size passenger EV – mid-size car
Nissan – Leaf 5 passenger EV – compact or mid-size car
Ford Transit Connect EV - light commercial delivery van

**Medium Duty Commercial (does not seem as firm as LDVs)**

Daimler Sprinter PHEV delivery van
Eaton Plug-in “Trouble Truck” for Electric Utilities

**Note: Tax credits for 4-16 kWh of battery capacity to 2014 support light LDVs**

# *Federal Support for Electric Drive Is Extensive*

**Johnson Controls, Inc**. $299.2 million grant (supplies nickel cobalt aluminum lithium ion pack type to Mercedes – the first lithium-ion HEV pack)

**A123 Systems** $249.1 million grant (A123 owns "Hymotion" supplier of the Prius retrofit [PHEV] pack, using lithium iron phosphate battery chemistry).

**General Motors** $240 million grant. Supports the Volt Pack, using manganese oxide lithium ion battery chemistry.

**EnerDel/Ener1** $118.5 million grant. Specializes in the manganese oxide plus titanate lithium ion battery chemistry.

**Dow Chemical** of Midland, Michigan receives a grant of $161 million. Dow will work with Kokam (Korea) on a "superior lithium polymer battery" (SLPB).

**Nissan** has been given a $1.6 billion low interest loan guarantee for an electric vehicle and battery manufacturing plant in Smyrna, TN.

**Tesla Motors** has also been awarded a low interest loan of $465 million, which it will use to produce the Model S (an EV sedan)

## *Current Clean Cities Support of Electric Drive*

- Reported 102,000 HEVs/632,000 AFVs in 2008, Displacing 12M GGEs or 4% of Coalitions' Total Petroleum Displacement.
- Clean Cities ARRA funding will support 1,539 electric stations and numerous HEVs and Heavy-Duty Electric Hybrids.
- Clean Cities jointly funds the Fuel Economy.gov web site.
- Clean Cities' Alternative Fuels and Advanced Vehicle Data Center includes portals on both HEVs and PHEVs.
- Clean Cities conducts outreach events to promote HEVs and educate the public about PHEVs.

## *What Can Clean Cities Do to Enhance Opportunities?*

***Carefully consider figures of merit to present to potential purchasers. Focus on fuel savings per year via number of full charge depletion events/yr.***

***Evaluate having default comparisons for "compare side-by-side" on fueleconomy.gov use probable fuel consumption avoided per kWh.***

***Work with state governments and OEMs to develop and implement standard procedures for installing and/or inspecting new and upgraded charging circuits.***

***By carefully monitoring fleets, assist manufacturers in locating and addressing modes of failure as promptly as possible, so that they may be addressed.***

***Monitor early charging behavior for purposes of:***

***(1) Matching compatible consumers and PHEV configurations, determining cost effectiveness of level 2 upgrades in garages and at carports***

***(2) Determining best public, workplace and retail locations and charging level***

***Study the relative viability of plug-ins when systematically integrated into new construction vs. when retrofitted — at houses, apartments, workplace, etc.***

# Argonne National Laboratory
# Center for Transportation Research

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- Marcy Rood Werpy at mroodwerpy@anl.gov

# Conclusions

- Electricity generation is based on domestic fuels (1.2% oil).
- Electric drive can sharply reduce tailpipe and WTW GHG emissions, significantly enhance sustainability, enhance viability of renewables (wind and solar).
- The residential market up to mid-size cars & crossover SUVs is targeted for P-HEVs
- Li-ion battery energy & power densities make P-HEVs plausible. $/kWh is still high.
- P-HEVs can be designed for either all-electric or blended (low battery power) charge depletion. Low kW/kWh ratios reduce $/kWh cost.
- Durability and useable capacity are major battery challenges.
- The target niches are (1) smaller vehicles in garages and carports, charged overnight with existing plugs (2) city and sports EVs with new charging infrastructure, daytime fast charging services
- Incentives for P-HEVs are probably adequate to jump start the market