GLOBAL PROSPECTS OF PLUG-IN HYBRIDS

Rob Winkel and Robert van Mieghem, Netherlands

TNO Automotive

Operating Agents, Annex VII "Hybrid Vehicles"

IEA HEV/EV Implementing Agreement

Dan Santini, USA
Argonne National Laboratory

Mark Duvall, USA
Electric Power Research Institute

Co-managers, Task 2, Plug-in Hybrid Vehicles

Valerio Conte, Austria
Arsenal Research

Mats Alaküla, Sweden
Lund University

François Badin, France
INRETS

R. Bleis, France
EDF

Patrick Debal, Belgium
VITO

Arie Brouwer, Netherlands
SenterNovem

ELECTRIC POWER RESEARCH INSTITUTE

Argonne NATIONAL LABORATORY

... for a brighter future

This presentation has been created by an employee of Argonne National Laboratory, a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC, under Contract No. DE-AC02-06CH11357 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government

U.S. Department of Energy

UChicago Argonne LLC

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

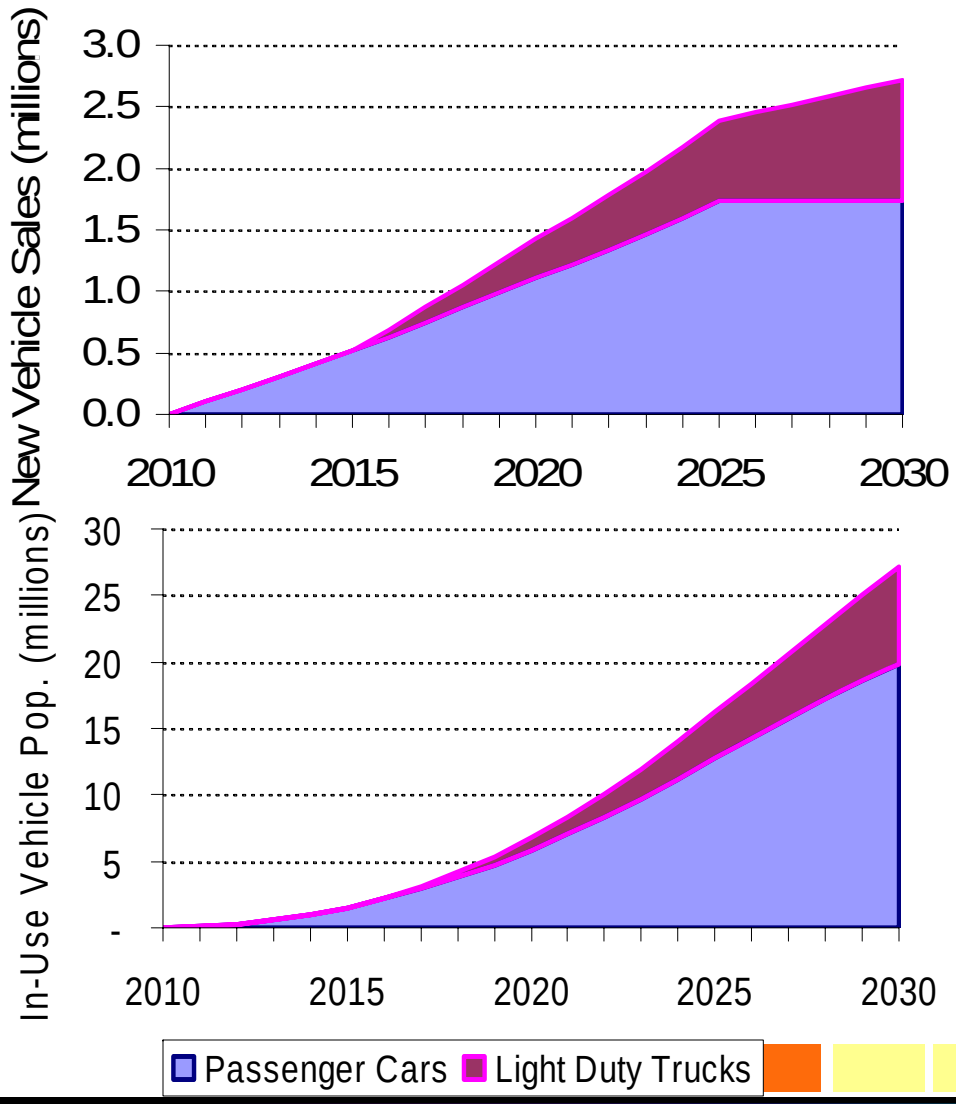
Evolution of Batteries, Motors and Engines Slowly led to Today's Compact, Efficient Parallel Hybrid Powertrains. Continuation of Established Trends, Adapting Parallel HEVs With Small Batteries, will Lead to Successful PHEV Powertrains

Paper Topics and Issues (presentation topics in bold):

- **Electricity supply: infrastructure adequacy, power plant types used**
- **Oil use & GHG emissions reduction;** energy security
- **Marketability, consumer preference**
- **Batteries: charging;** lifetime; charge acceptance; **power/energy (Ni-MH & Li-ion**); HEV vs. **PHEV charge depletion & design**
- **Recent PHEV technology history**
- **Powertrain types;** CARB ZEV credit regulations; kW rating issues
- Purpose built HEV vs. converted conventional

Electricity supply: infrastructure adequacy, power plant types used

EPA Initial Evaluation: PHEV32km Rollout Scenario



- Passenger vehicle fleet: PHEVs start penetrating in 2011 and grow to 15% of passenger vehicle sales by 2030

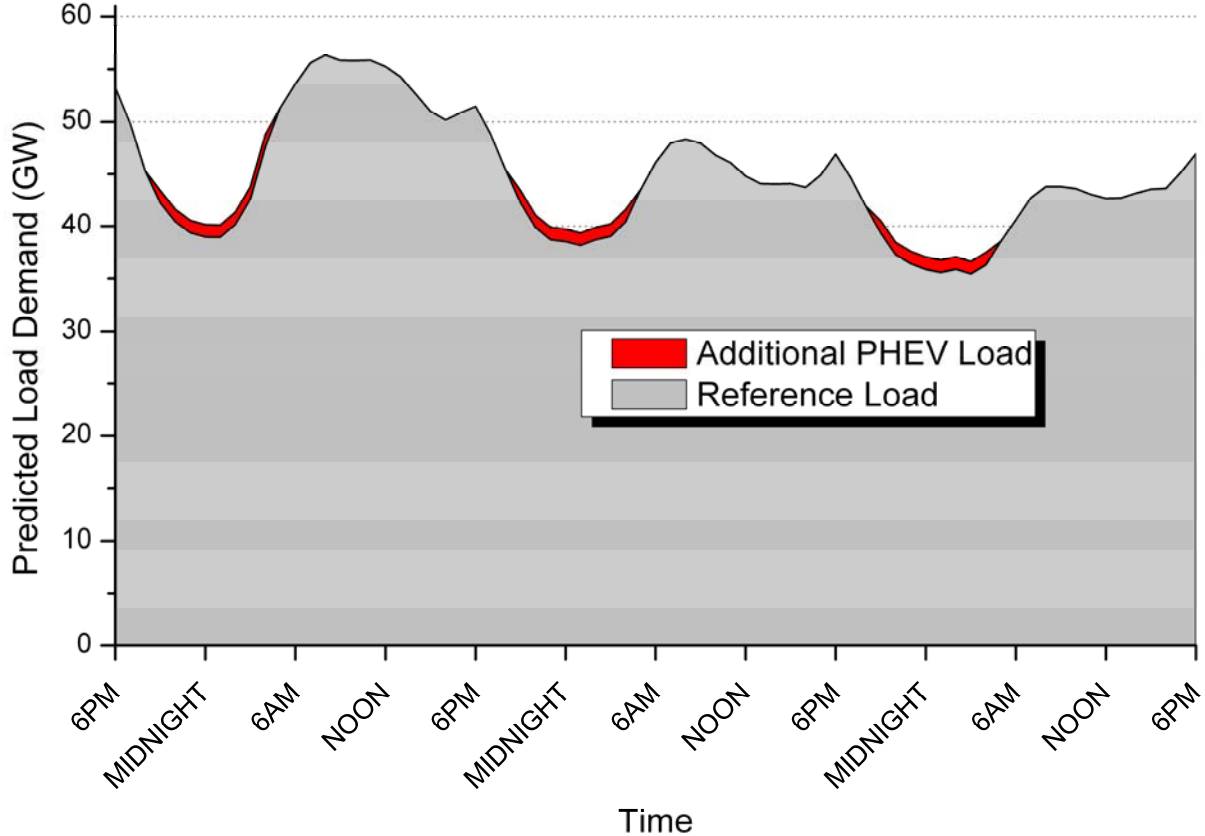
In 2030:

- Annual sales reach 2.7 million PHEVs
- 27 million PHEVs on the road (9% of the nearly 300 million vehicles)

By comparison:

- Conventional hybrids represented 1.2% of all U.S. sales in 2005 (~ 5% by 2010)

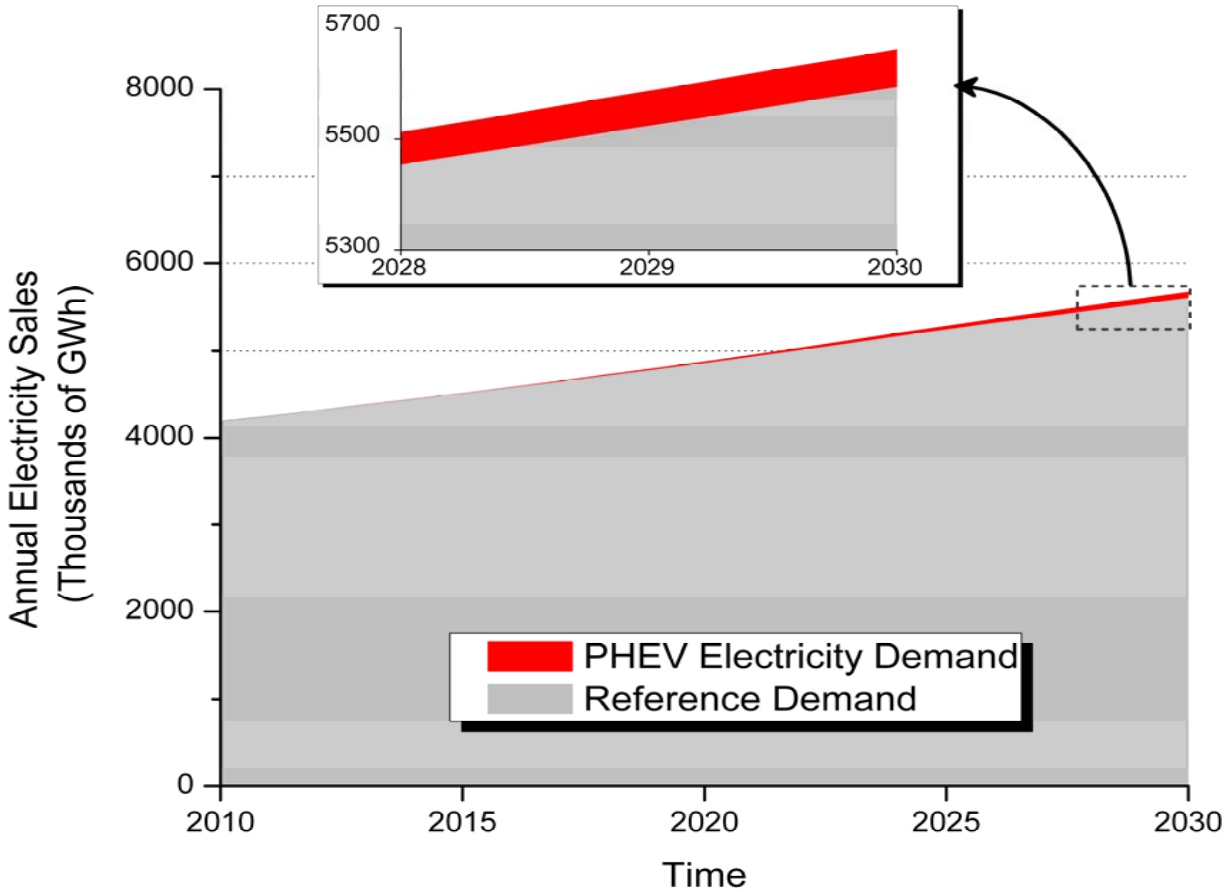
PHEV Electricity Demand Likely in Off-Peak



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

Model: IPM

Electricity for PHEVs in U.S. EPA's Rollout Scenario

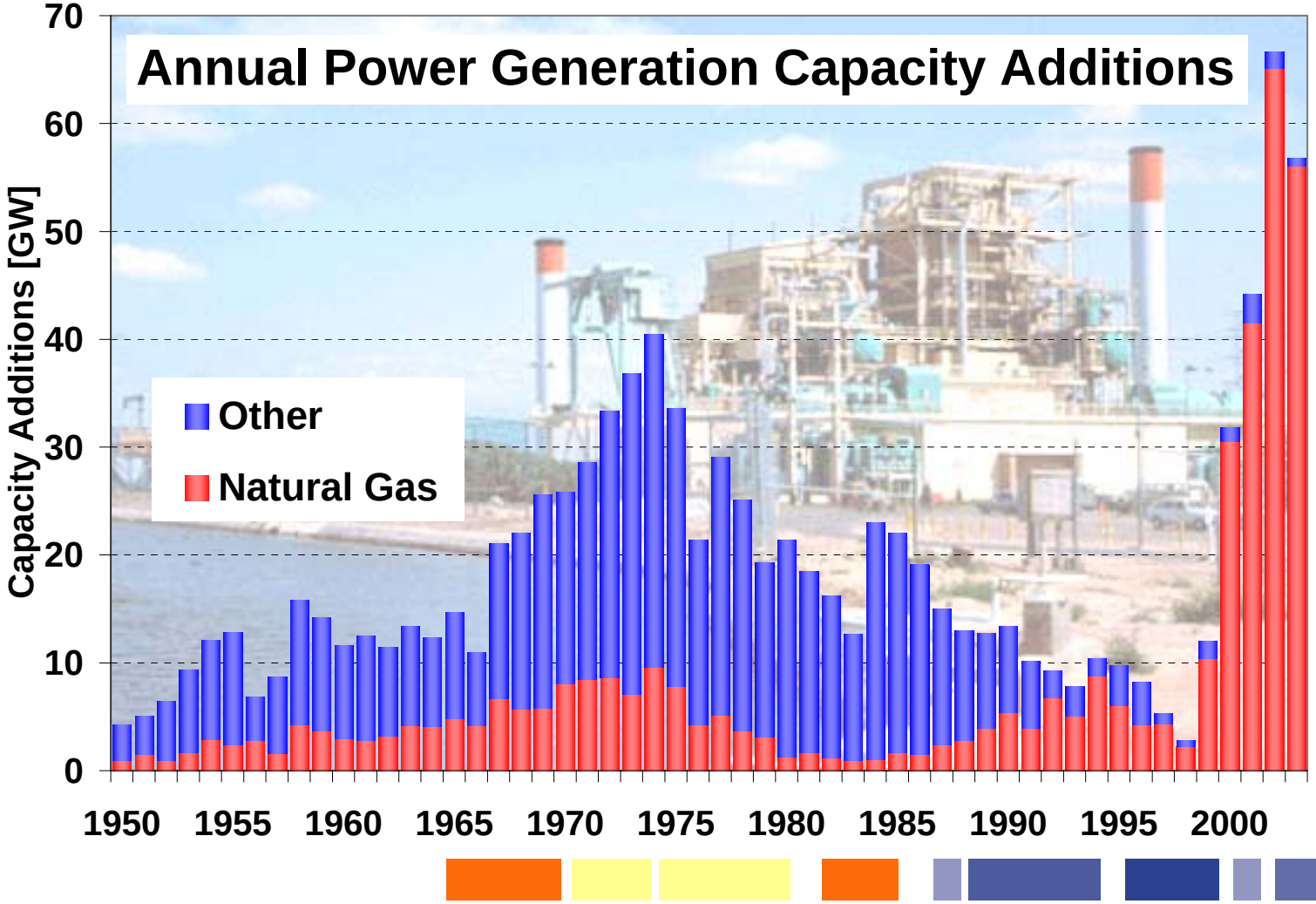


- Electricity sales from PHEVs represent a small fraction of total U.S. electricity demand (In 2030, 1.2% of demand is from PHEVs)

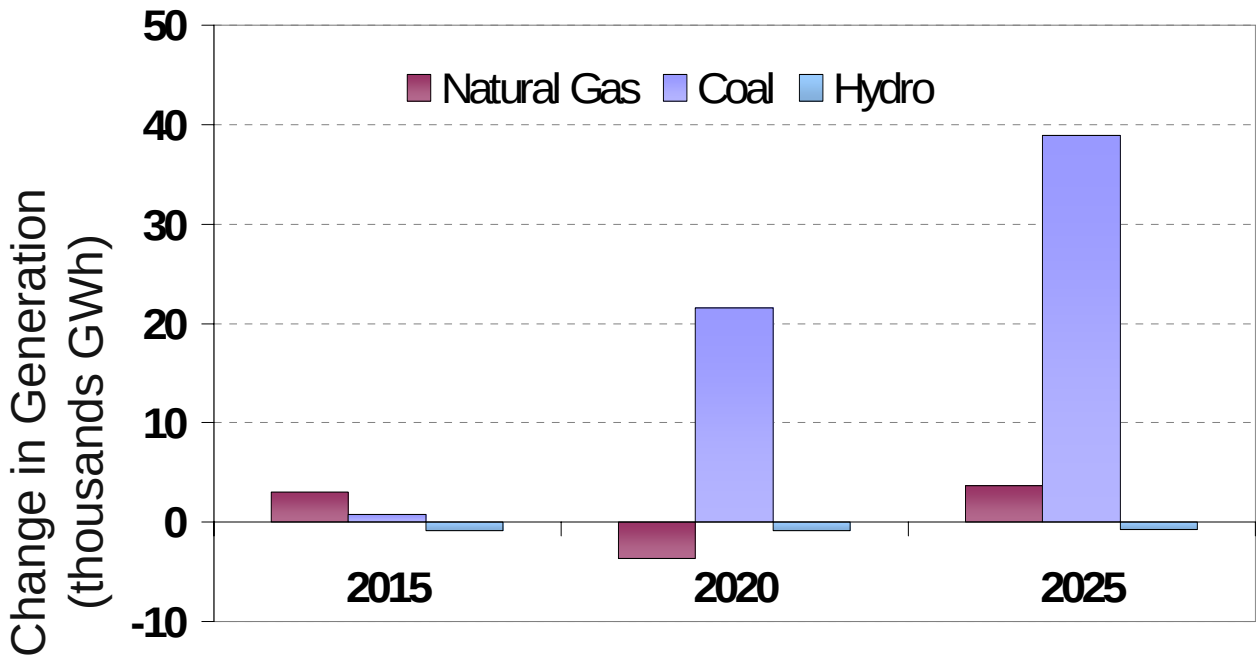
Model used: IPM

What is Available for Use in the Short-Term?

U.S. Natural Gas Generating Capacity Jumped After 2000



EPA's Model Predicts Natural Gas to Fuel Added Electricity Generation for the Next Decade's PHEVs, Coal After. Even if Coal is the Fuel, GHGs are Reduced by PHEVs



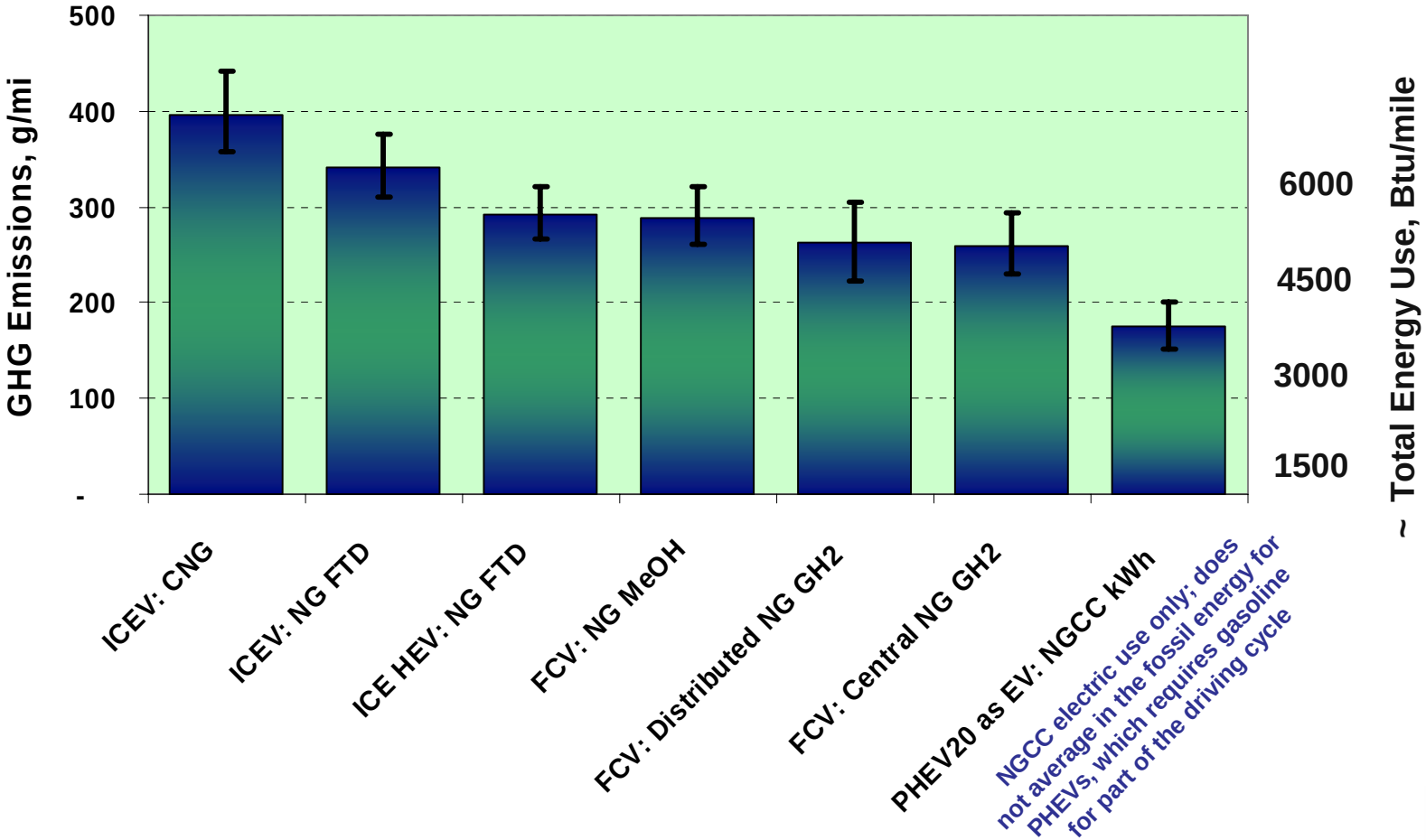
	2011-2030 Cuts MMT CO_2e	In 2030: % Cut vs. Base
Hybrids	390	2.5%
PHEVs	450	2.9%
PHEVs +CCS	770	5.1%

CCS = carbon capture and storage
CO2e = carbon dioxide equivalents

- By 2020, increased generation is from coal
- Additional generation initially natural gas fired plants

Model: IPM

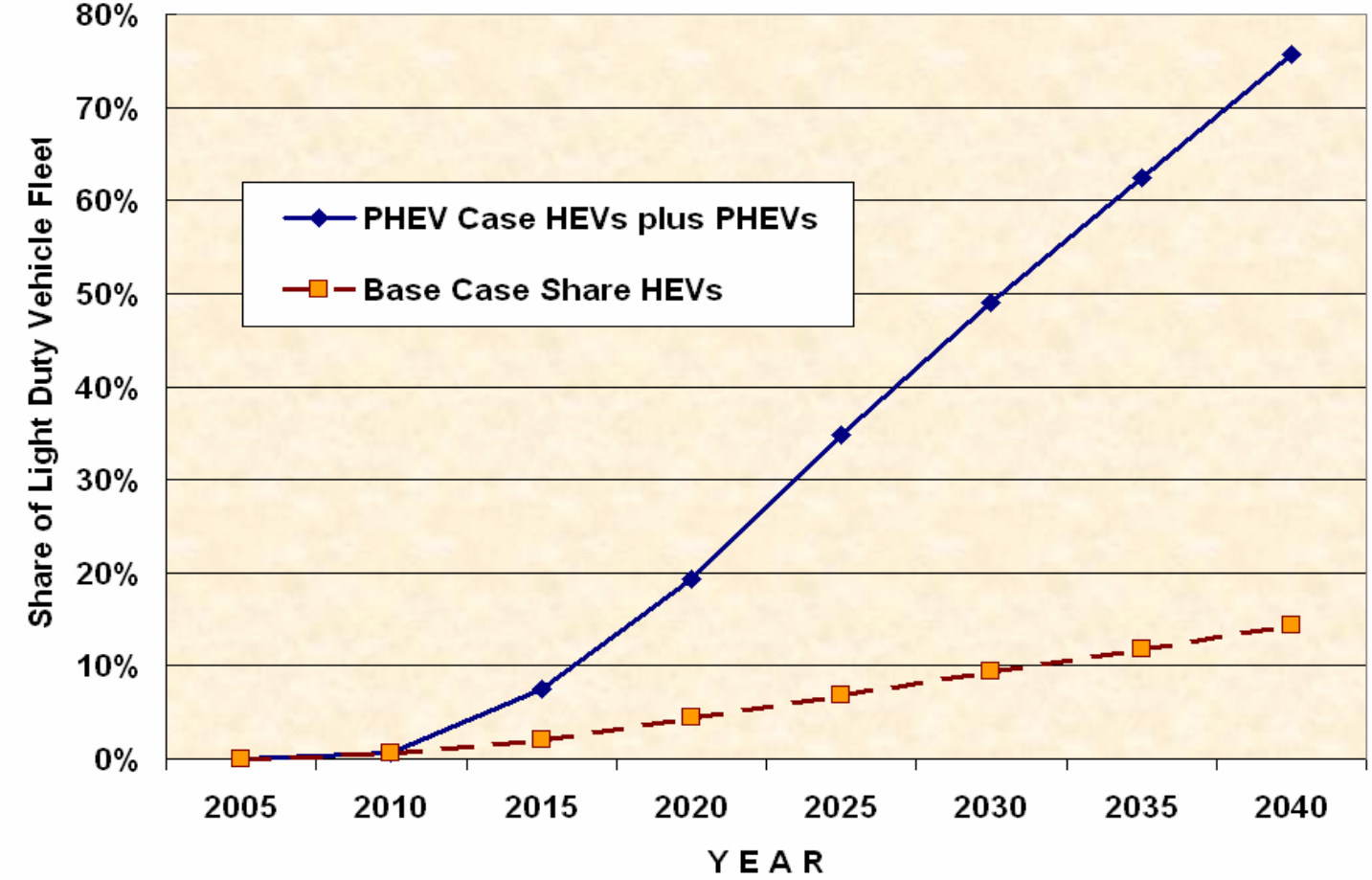
If Natural Gas is Used to Create Vehicle Fuels, NGCC-derived Electricity for PHEVs Can Result in Less Depletion of Natural Gas, Less GHGs/Mile



Courtesy of Y. Wu and M. Wang, Argonne. Results are early project results, not yet generally available from the authors. This slide was hidden (not used) in the "as-delivered" presentation.

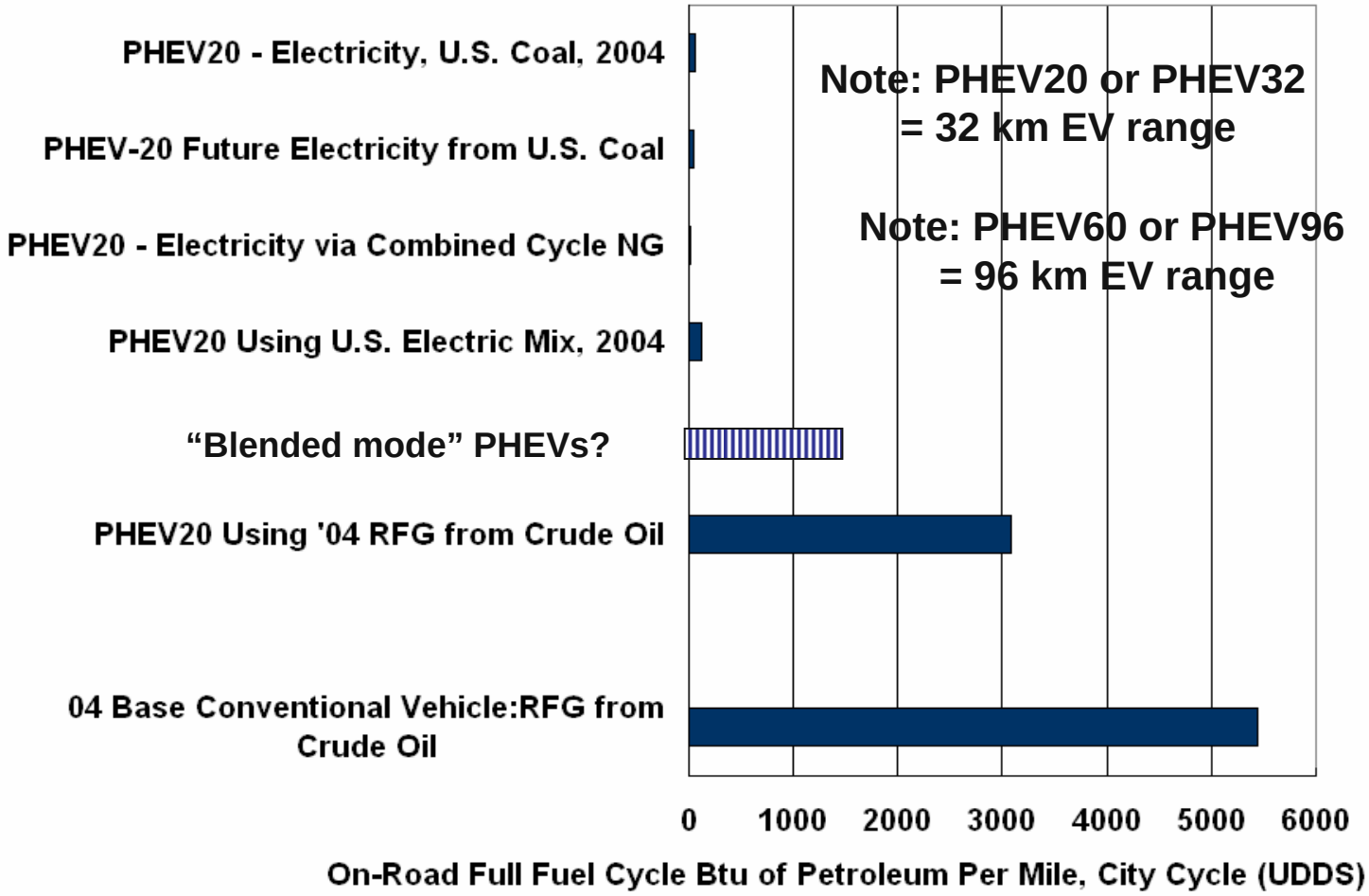
Oil use & GHG emissions reduction

D. Hanson of Argonne and P. Balash of the National Energy Technology Lab Examined Dramatic Growth of PHEVs to 2040

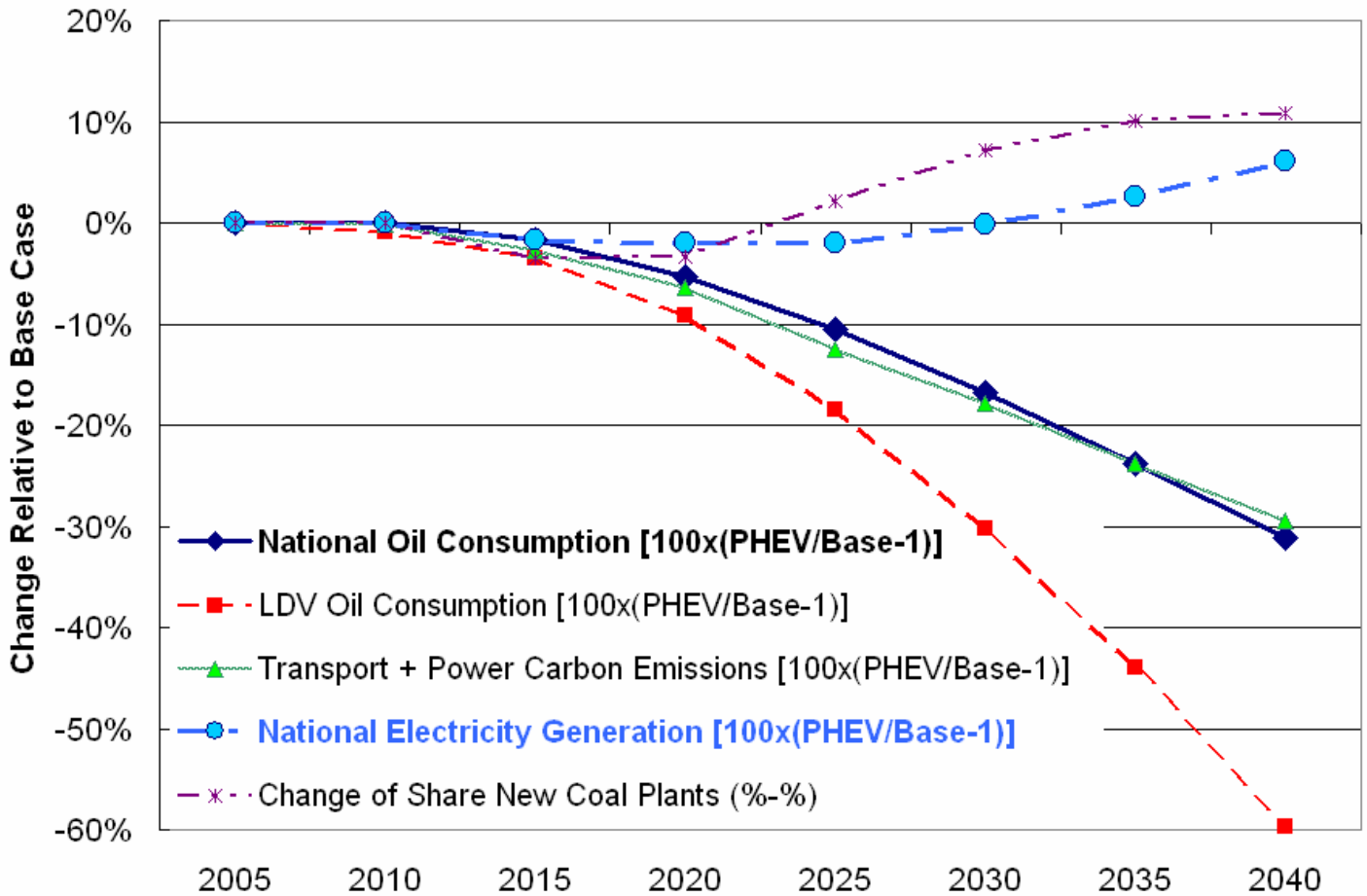


AMIGA Scenario by Hanson and Balash

Theoretical Oil Savings, 2001 EPRI Study: Each PHEV (Full HEV) Sharply Reduces Oil Use - Far More if Electricity is Used



Hanson & Balash also Predict More Coal After 2020, but Predict Success for Wind, and Lower Net Carbon w Advanced Coal Technology



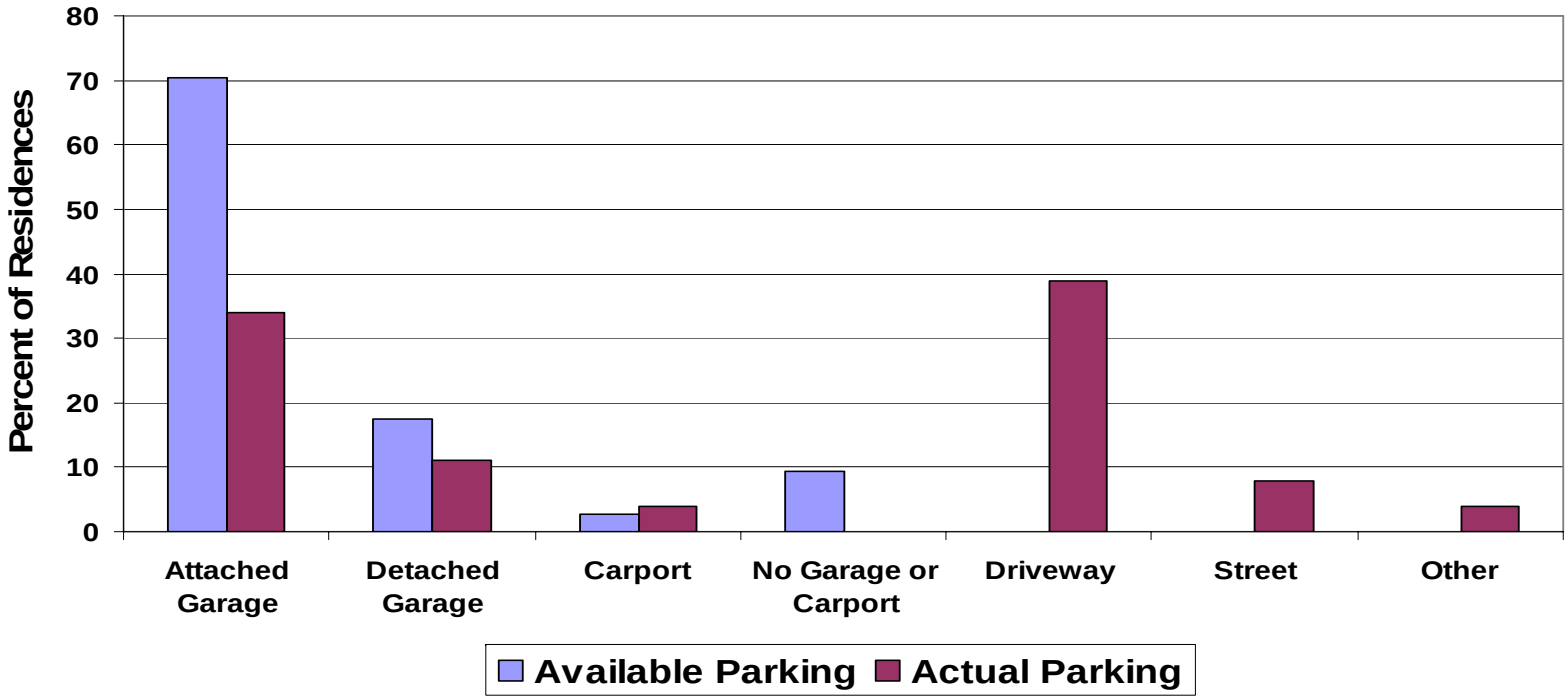
Change Relative to a Base Case Without PHEVs

- **Marketability, consumer preference**
- **Battery charging in the initial target market**
  - **where (garages, single family homes)**
  - **when (off-peak)**
  - **how (1-2 kW chargers, several hours)**
- **Once the kWh are in the battery, what is the least cost way to get them out?**

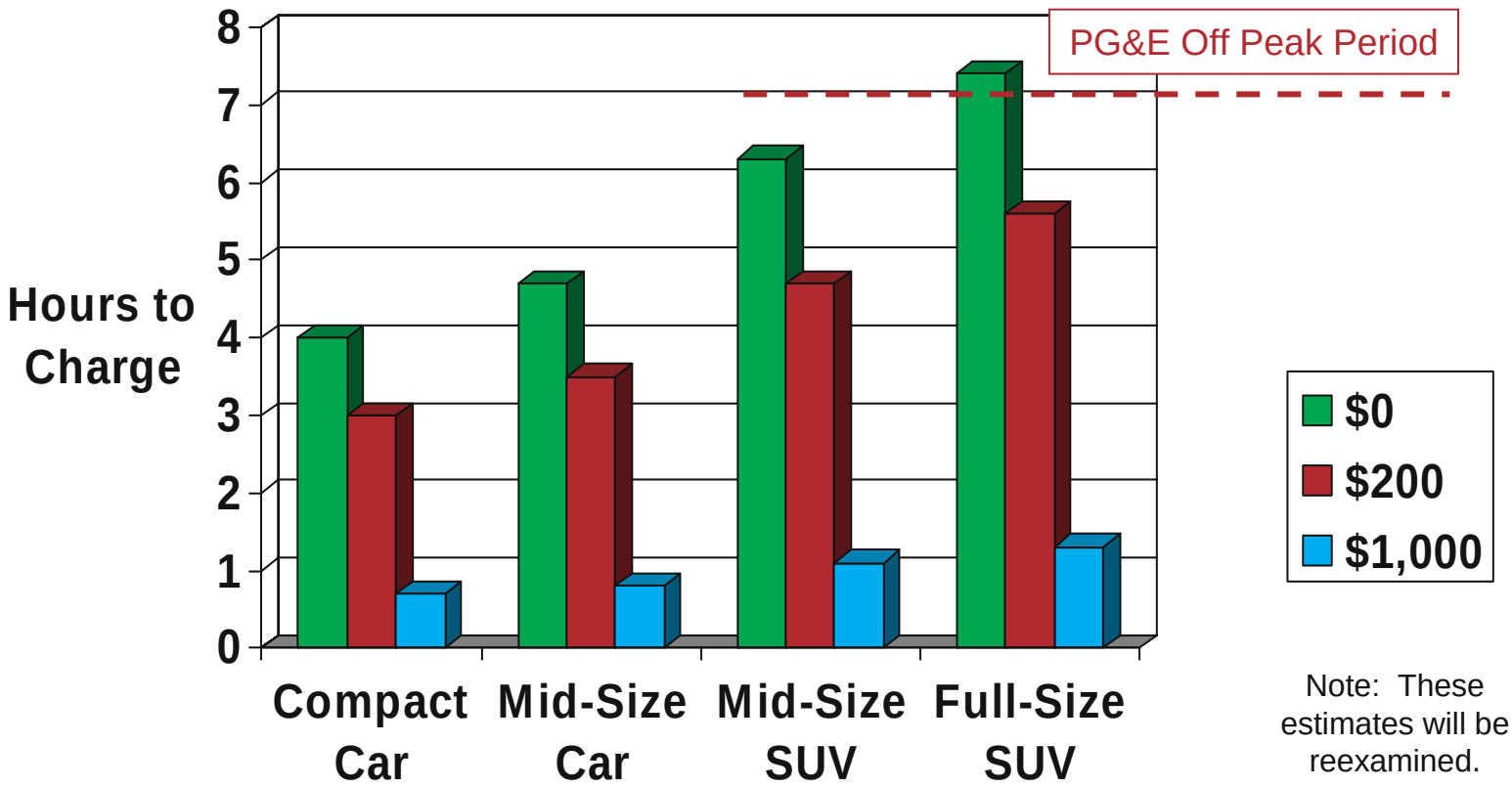
More than 30% of Present U.S. Households Park their Most Used Vehicles in a Garage or Carport

Available Parking Facilities and Actual Parking (of the most used vehicle) for People in Detached Residences

(59% of all U.S. households live in detached residences)



Even With No Infrastructure Investment (on Board Vehicle Charger), PHEV32kms in Garages and Carports Charge Overnight



Note: These estimates will be reexamined.

EPRI Estimate of Infrastructure Cost vs. Hours to Charge

Initial Charging Infrastructure

- Plug-in hybrids require relatively low power charging
- Wide availability of infrastructure
  - Initial focus on private chargers
- Array of options
  - 120 VAC, 15 amp (~1.4 kW)
  - 120 VAC, 20 amp (~2.0 kW)
  - 208/240 VAC, 30 amp (~6 kW)
- 120 VAC strongly preferred due to cost, availability

PHEV 20 Vehicle	Pack Size	Charger Circuit	Charging Time 20% SOC
Compact Sedan	5.1 kWh	120 VAC / 15 A	3.9 – 5.4 hrs
Mid-size Sedan	5.9 kWh	120 VAC / 15 A	4.4 – 5.9 hrs
Mid-size SUV	7.7 kWh	120 VAC / 15 A	5.4 – 7.1 hrs
Full-size SUV	9.3 kWh	120 VAC / 15 A	6.3 – 8.2 hrs

1.2 – 1.4 kW power, 1 or 2 hours conditioning

Example: PG&E's TOU Summer time periods

	12am		7am		2pm		9pm	12am
Monday	Off peak		Partial Peak		Peak			Partial Peak
Tuesday								
Wednesday								
Thursday								
Friday								
Saturday						Partial Peak		Off Peak
Sunday								

Pacific Gas and Electric Company

Source: S. Thesen, Electrical Service Options for Residential Customer EV and PHEV Users, 9/26/06, CARB ZEV Symposium

A CA Utilities Survey Shows $/kWh of Off- and On-Peak Rates

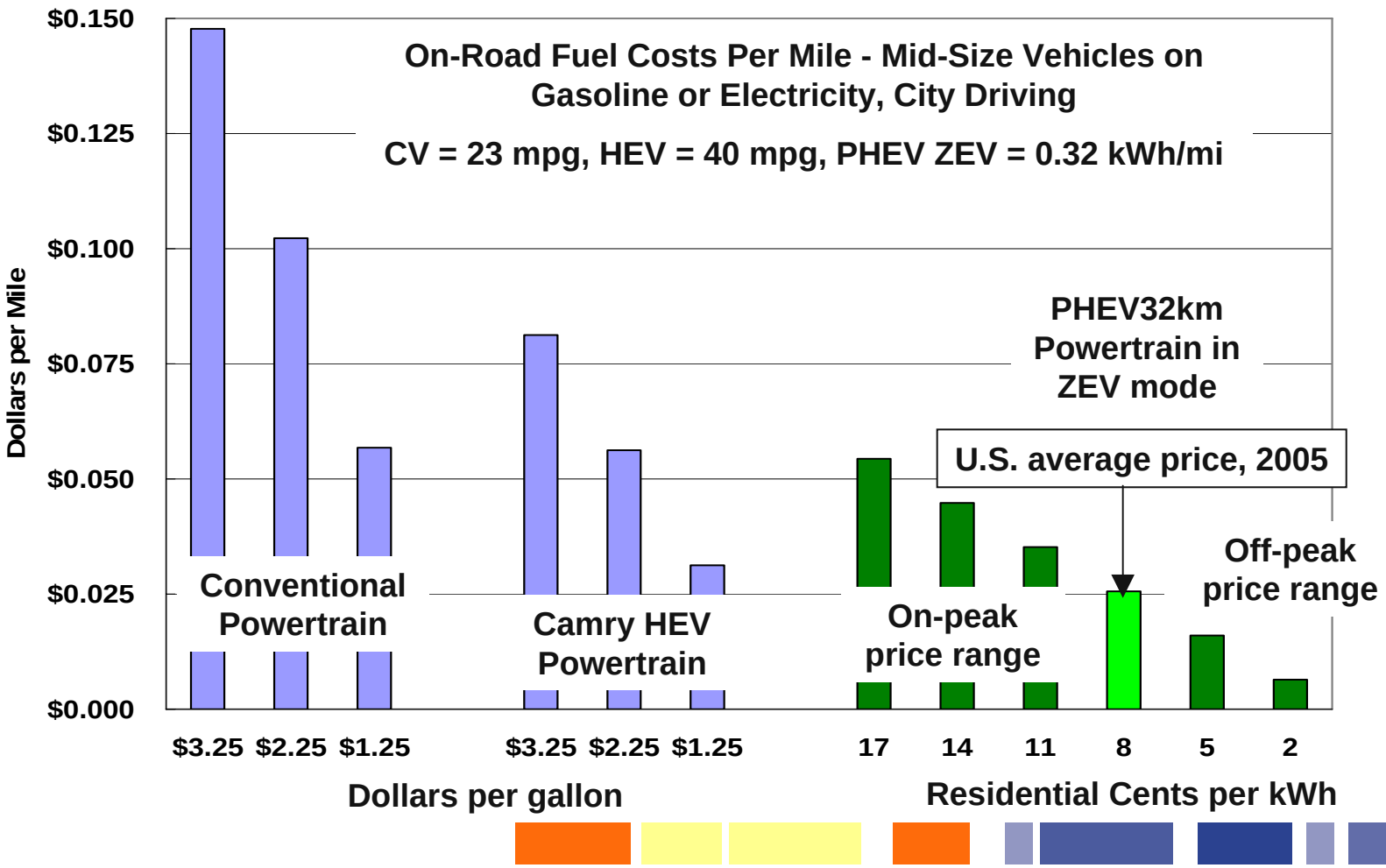
Minimum and Max Rates ($/kWh)

	Min	Max
Winter Off-peak	0.0468	0.0800
Winter On-peak	0.0664	0.1756
Summer Off-peak	0.0497	0.0800
Summer On-peak	0.0813	0.3300

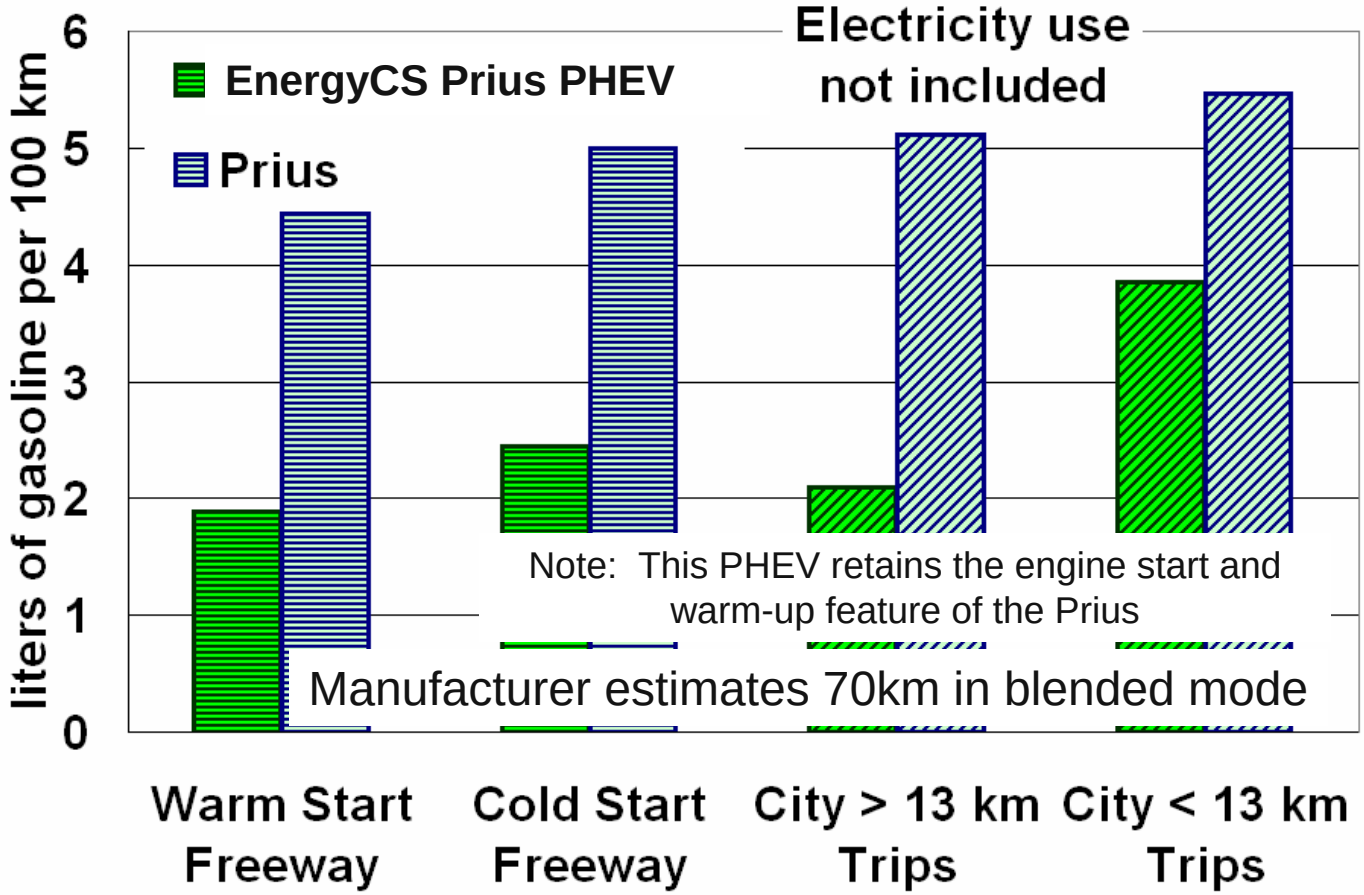
Pacific Gas and Electric Company

Source: S. Thesen, Electrical Service Options for Residential Customer EV and PHEV Users, 9/26/06, CARB ZEV Symposium

Savings from Off Peak Rates at and Below U.S. Average Prices Will be Important for Early PHEV Economic Viability.



First Field Tests of a Prius-Based PHEV on Blended Mode (ZEV Capability Limited) Imply Considerable Oil Reduction



Sacramento Municipal Utility District Summer Field Test Results (AC on)

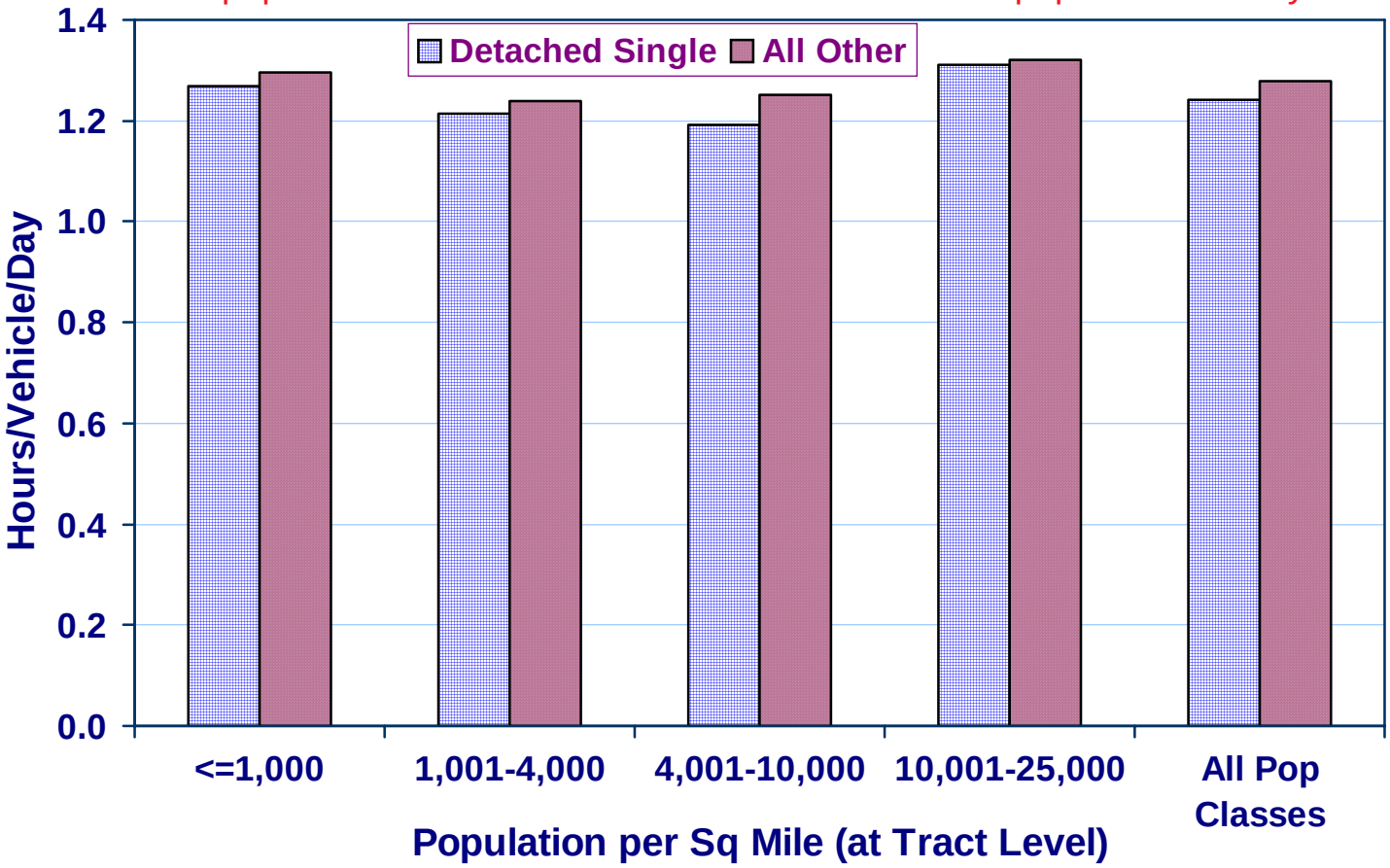
The Hymotion PHEV Conversion Adds a Li-ion Pack to the Existing Ni-MH Pack. With Less kWh it Has Less Distance to Depletion

System Descriptors, Hymotion L5	Attributes
Vehicle	Toyota Prius
Supplemental Energy Battery type	Lithium-ion
Energy in Plug-in Battery	5 kWh (~3.5 useful)*
Plug-in Battery Charge time	5.5 hrs / 4.0 hrs
Plug-in Battery Weight	72.5 kg
Estimated blended mode distance to battery depletion	**50 km** (31 miles)
Mfr's estimated fuel economy (gasoline + plug electricity) during blended mode	2.4 l/100 km (100 mpg)
Price	$9,500 for orders >100 $6,500 for order >1,000

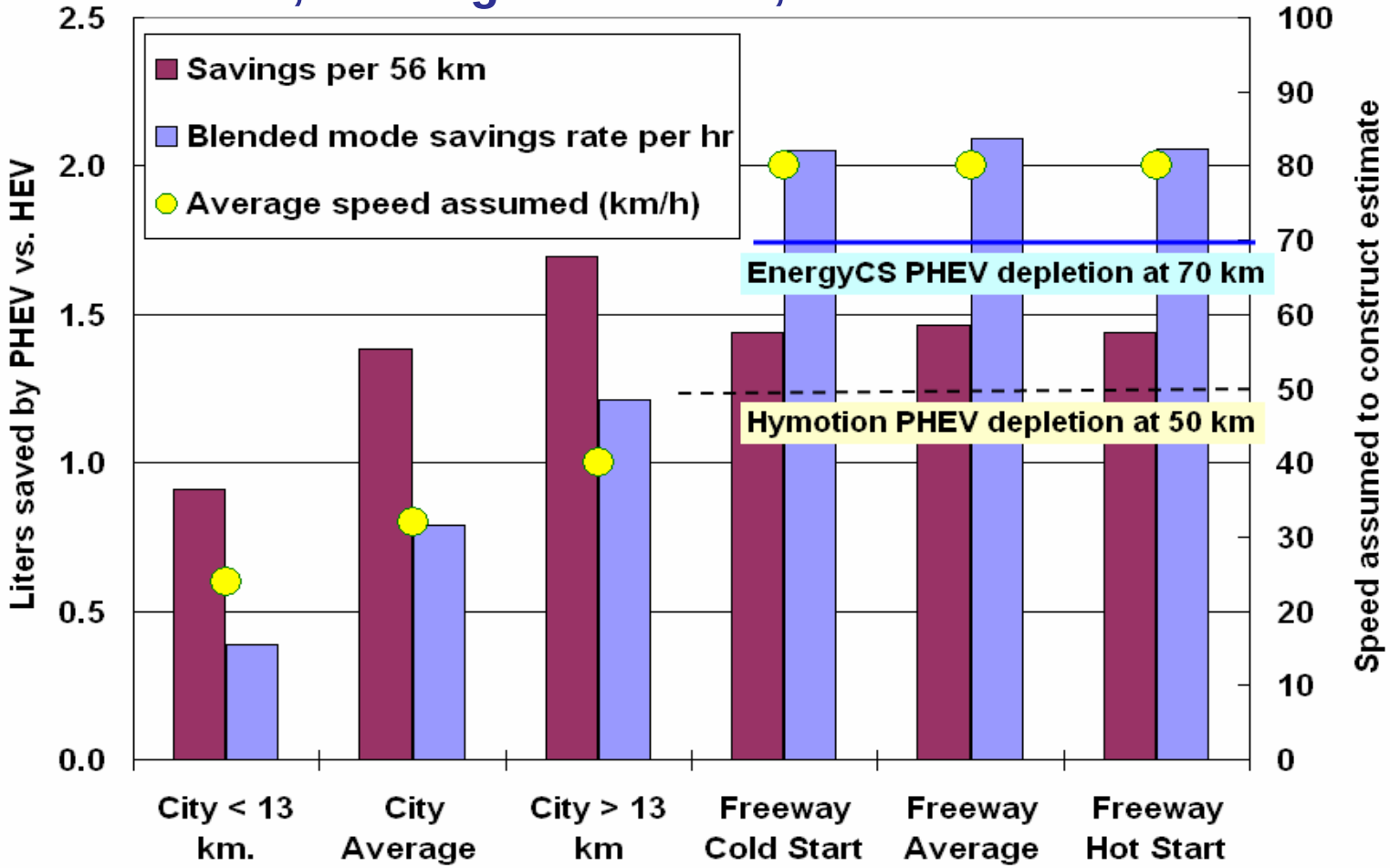
* **EnergyCS = 8.5 kWh (~ 6.5 useful)**

Average Hours of Use Per Day are Relatively Constant, Regardless of Density or Dwelling Type

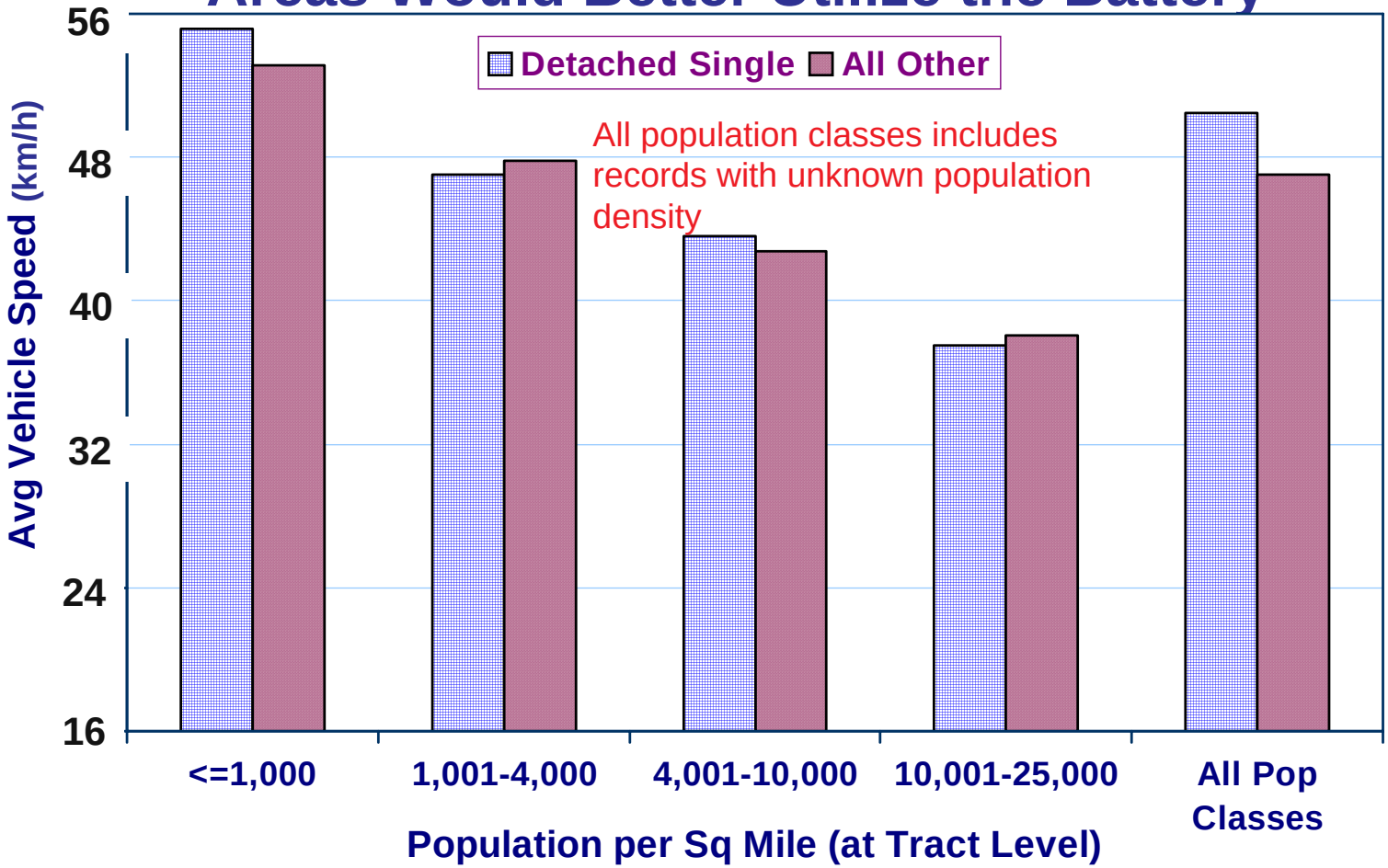
All population classes include records with unknown population density



For the EnergyCS Type of PHEV to Save Most Gasoline vs. a Prius, It Should be Used Where Average Driving Speeds are Higher – Suburbia, Uncongested Cities, and Rural America!

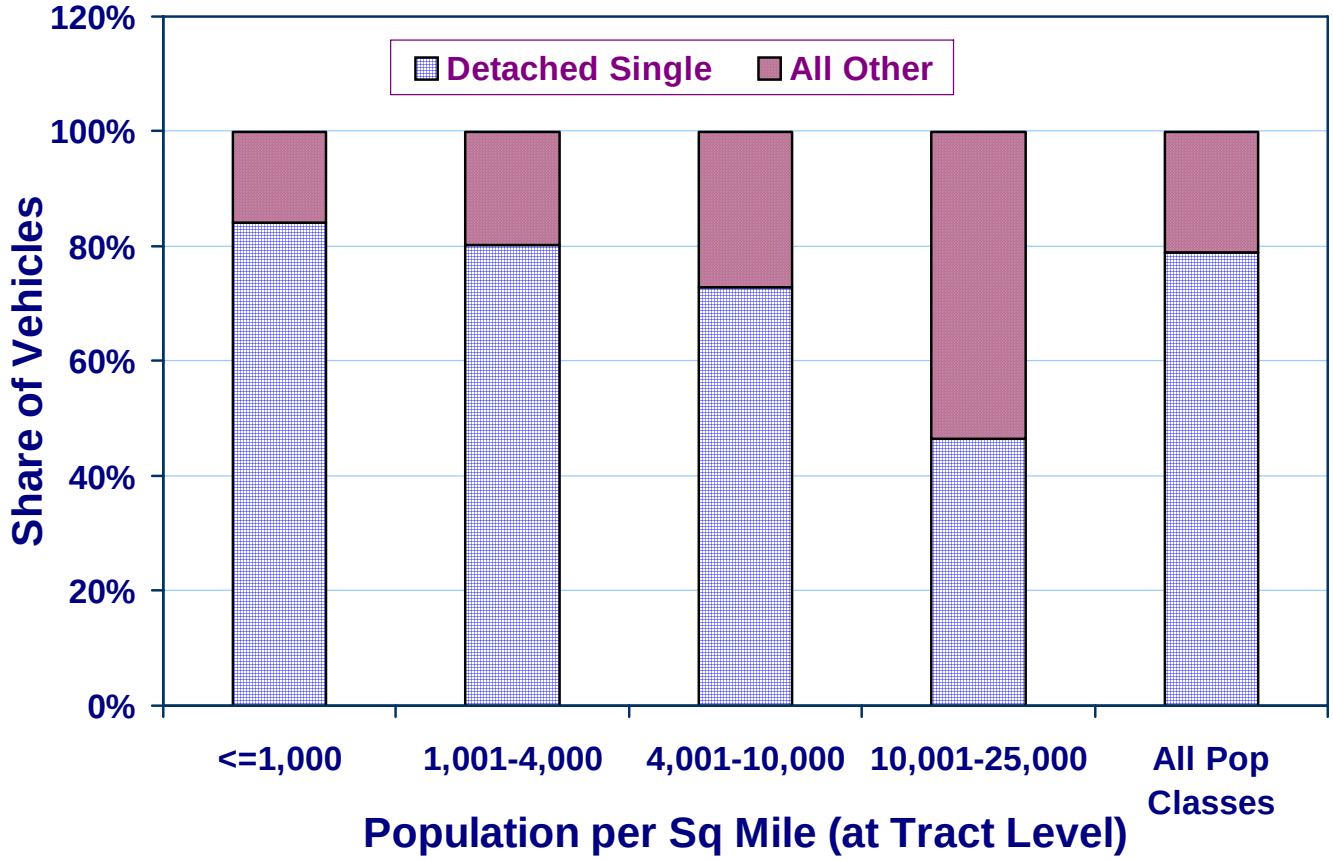


Since Faster Average Speed is Needed to Deplete the EnergyCS Prius in an Hour, Customers in Low Density Areas Would Better Utilize the Battery

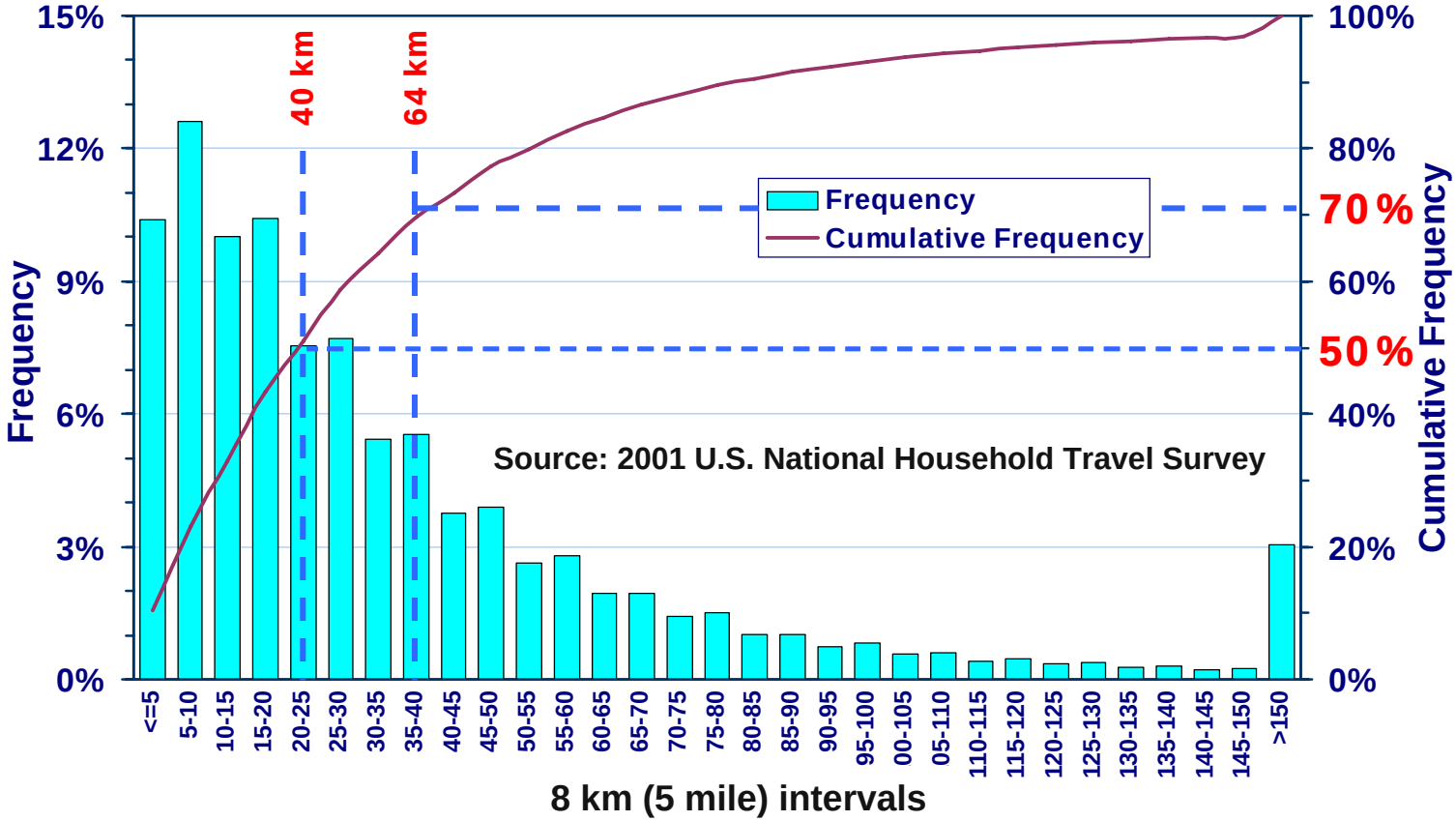


In Other Words, Where the Single Family Homes and Garages are Located

All population classes include records with unknown population density

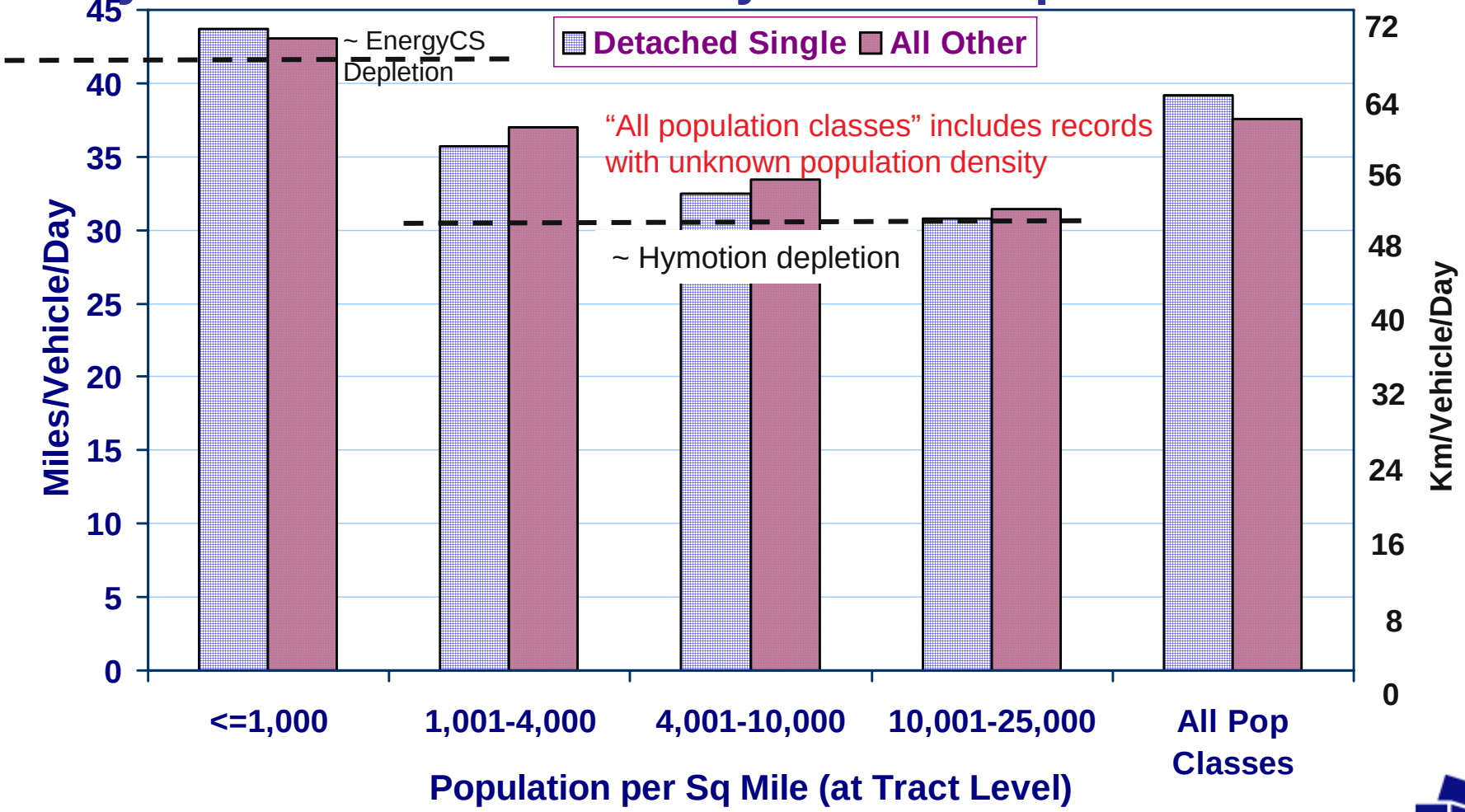


The "Blended Mode" Distance Capabilities of the EnergyCS and Hymotion Prius PHEVs Exceed Much U.S. Daily Driving

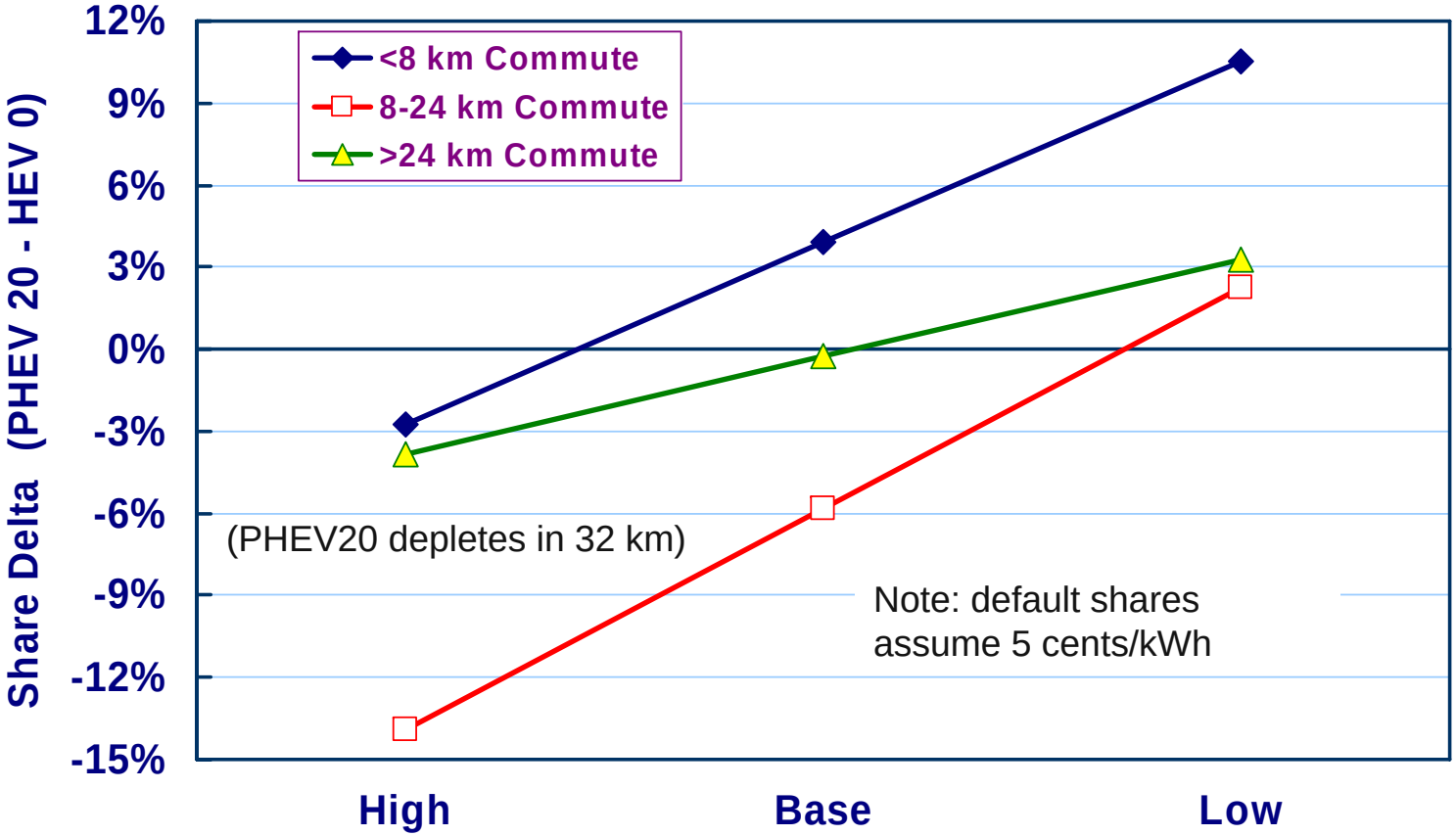


50% Travel ≤40 km./day; 70% ≤64 km./day

The Desire to Match Daily Driving and Distance to Depletion May Dictate Different Battery & Motor Options for PHEVs

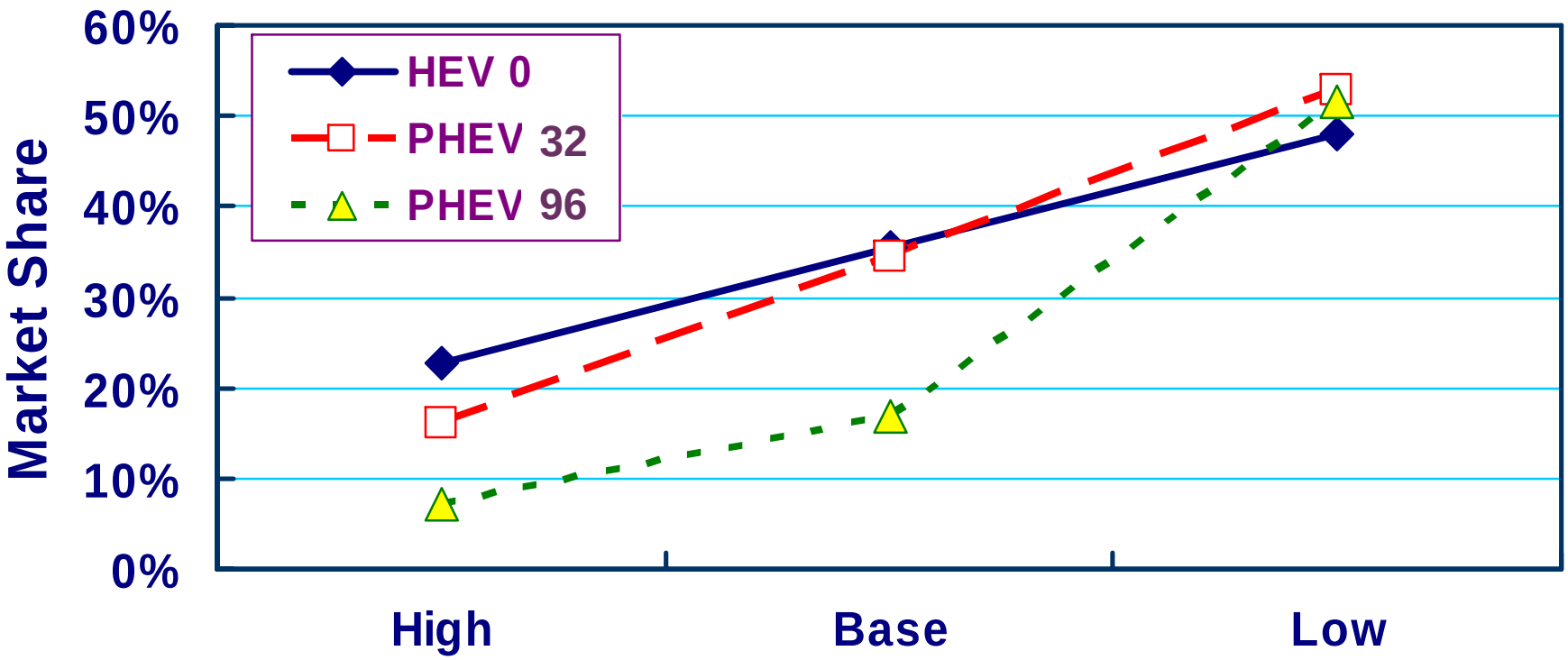


Those With Short Commutes in the EPRI 2001 Survey Had Most Interest in the PHEV that Charge Depleted in 32km



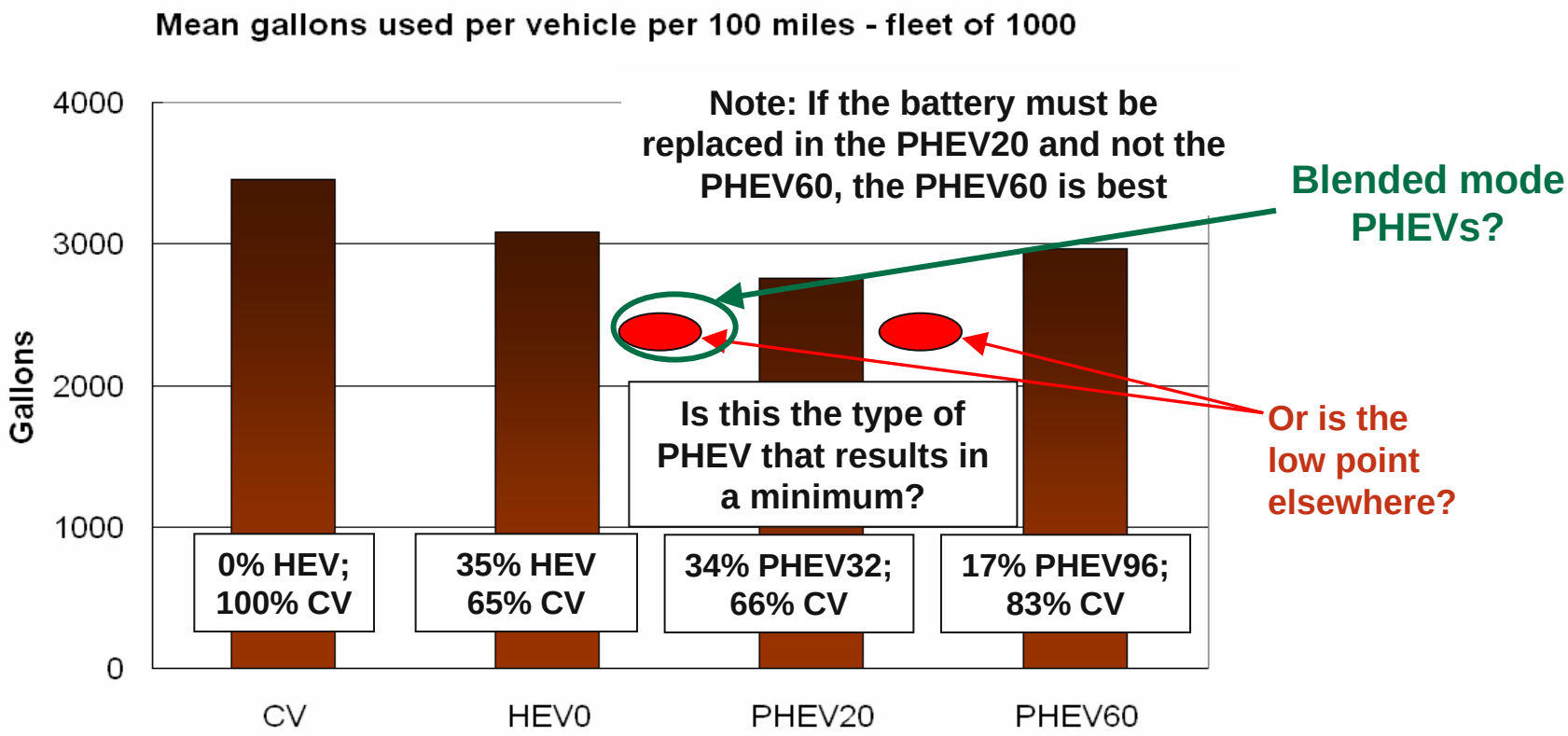
PHEV20 vs. HEV0 Market Share Difference vs. HEV Cost, by Commute Distance, EPRI 2001 Study

As Powertrain (Battery!) Costs Drop, EPRI Predicted Share of All Urban HEVs Rises; For Long Commutes, Low Cost Leads to Purchase of More ZEV Range



Time

Considering EPRI HEV Type Market Share Estimates, Which PHEV Would Save Most Oil?



Source: EPRI 1000349, 2001

Mid-size car – HEV powertrain paired against conventional (no other HEV competitor)

1970s-2005 PHEV Technology History

HEV/PHEV Powertrain types; Series vs. Parallel

Batteries: Power and Energy Density Evolution

Plug-in Hybrids Have Become Possible Because of a Confluence of Events

- Via NiMH chemistry, cost per kW dropped sharply (kW/kg rose sharply)
  - (cost per kWh did not drop sharply, however)
- NiMH battery life with narrow SOC swings may be as long as car life
- The superiority of parallel over series hybrids has finally become clear
- Very small (in terms of kg and kWh) batteries (compared to those considered in 1970s and 80s) in parallel powertrains allowed
  - Engine off
  - Regenerative braking
  - Consistent operation of engines at most efficient rpm and load
  - Limited incremental cost for hybrids
- Efficient parallel hybrids were successfully commercialized, with EV option
- Li-ion battery volumetric energy density improved dramatically, allowing li-ion batteries to "fit" and aftermarket PHEVs to be "easily, cheaply" built

Despite a Major 1975 Study Indicating its Inferiority, the Series Hybrid Concept Was the Anticipated PHEV Powertrain in Most of the 1990s

- **1975 – "Should We Have a New Engine" (JPL SP 43-17, Vol.II)**

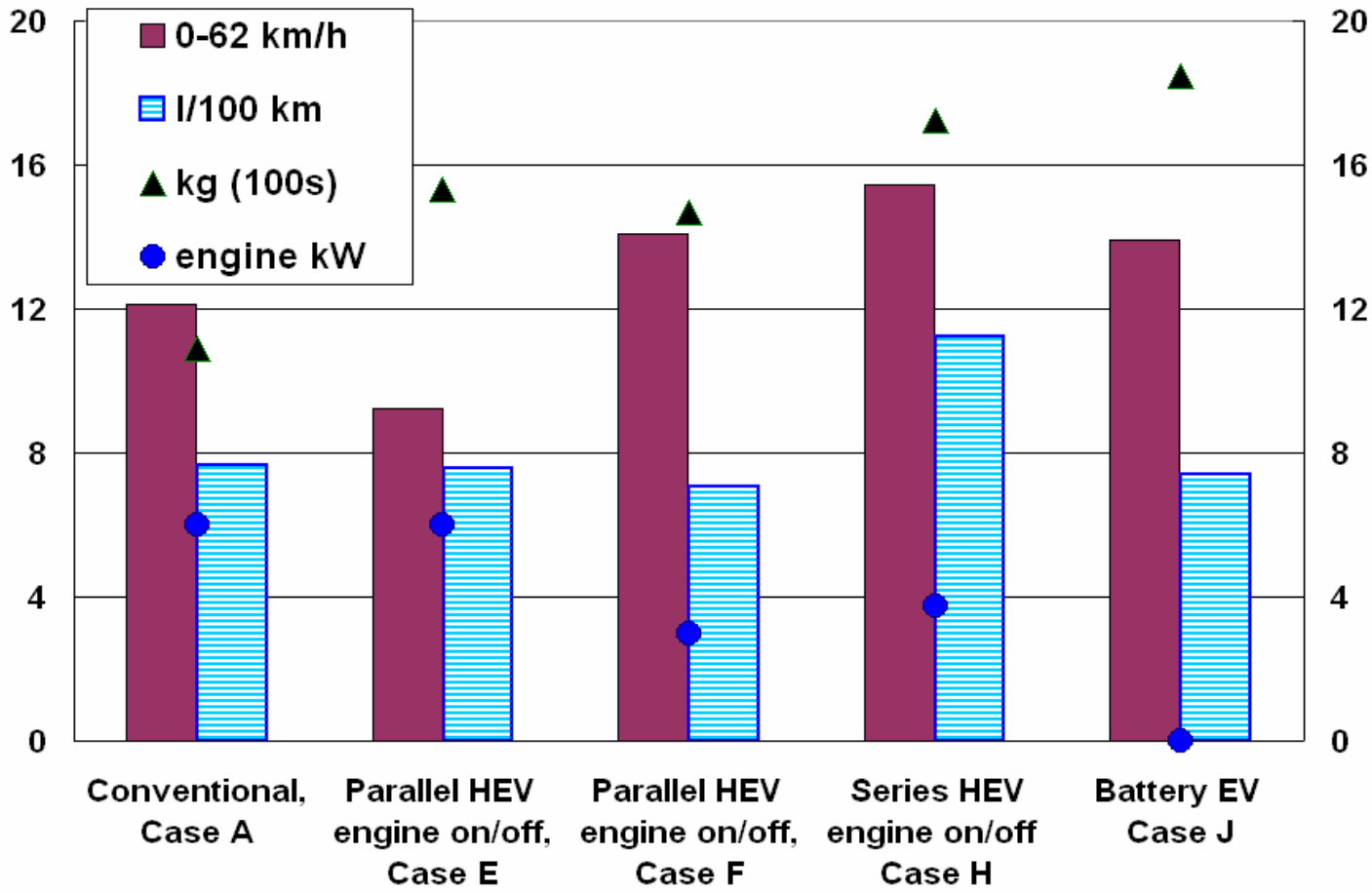
  "series hybrids are inferior to all other variations"

- **2000 – "a parallel hybrid with a more efficient engine and a small battery is the most reasonable and cost effective solution"**

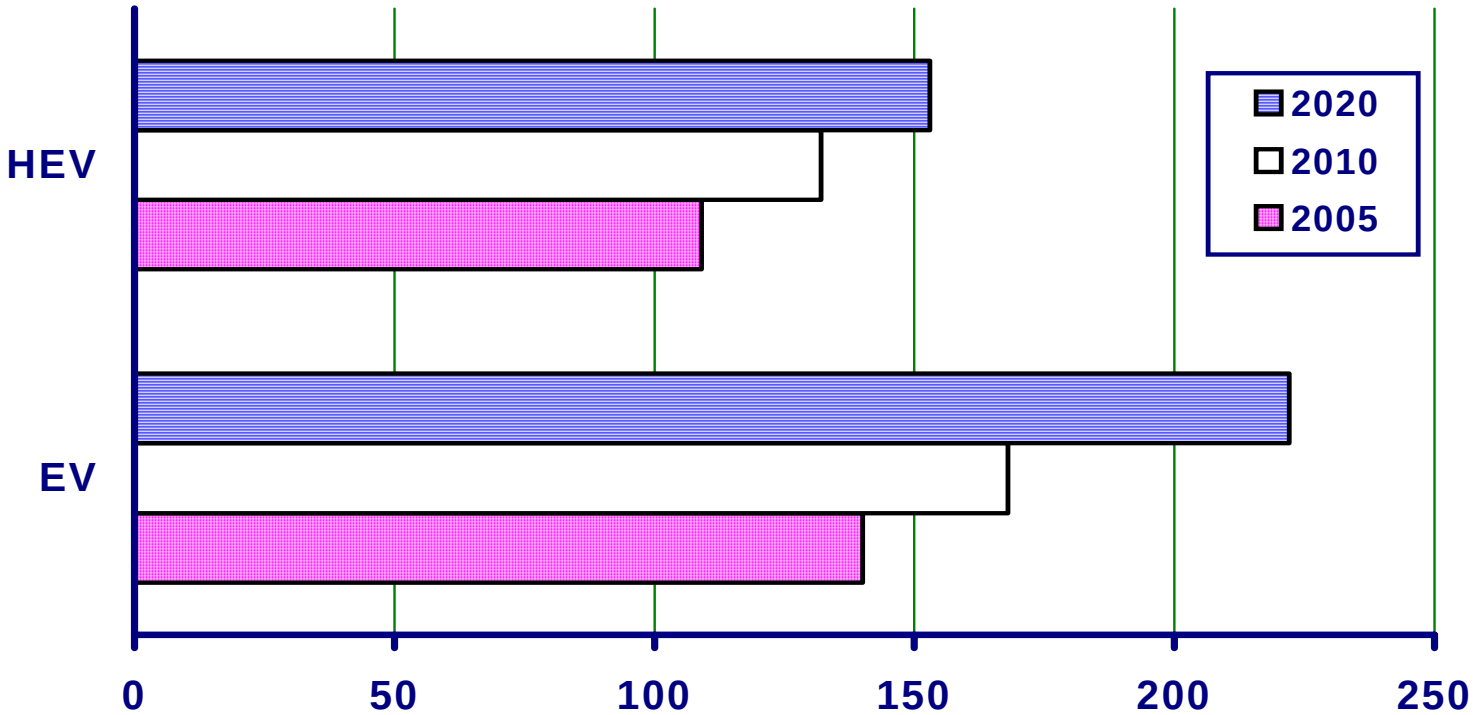
  Mueller et al, VW, as cited by Badin et al, EVS-18

- **2001 – "the combination of transmission, torque converter, and differential is more efficient than the series hybrid's shaft-to-wheel path …a parallel hybrid's electric motor will be significantly smaller than that required on a series hybrid … This yields a significant cost savings" (Plotkin et al, ANL/ESD/01-1)**

With PbA Batteries, the 1975 JPL Study Estimated Small Parallel HEV Fuel Use Reduction, Increases for Series HEVs



Projections By Experts in the Mid-1990s Implied Series Range Extender HEVs With Big Batteries, Long Distance EV Mode

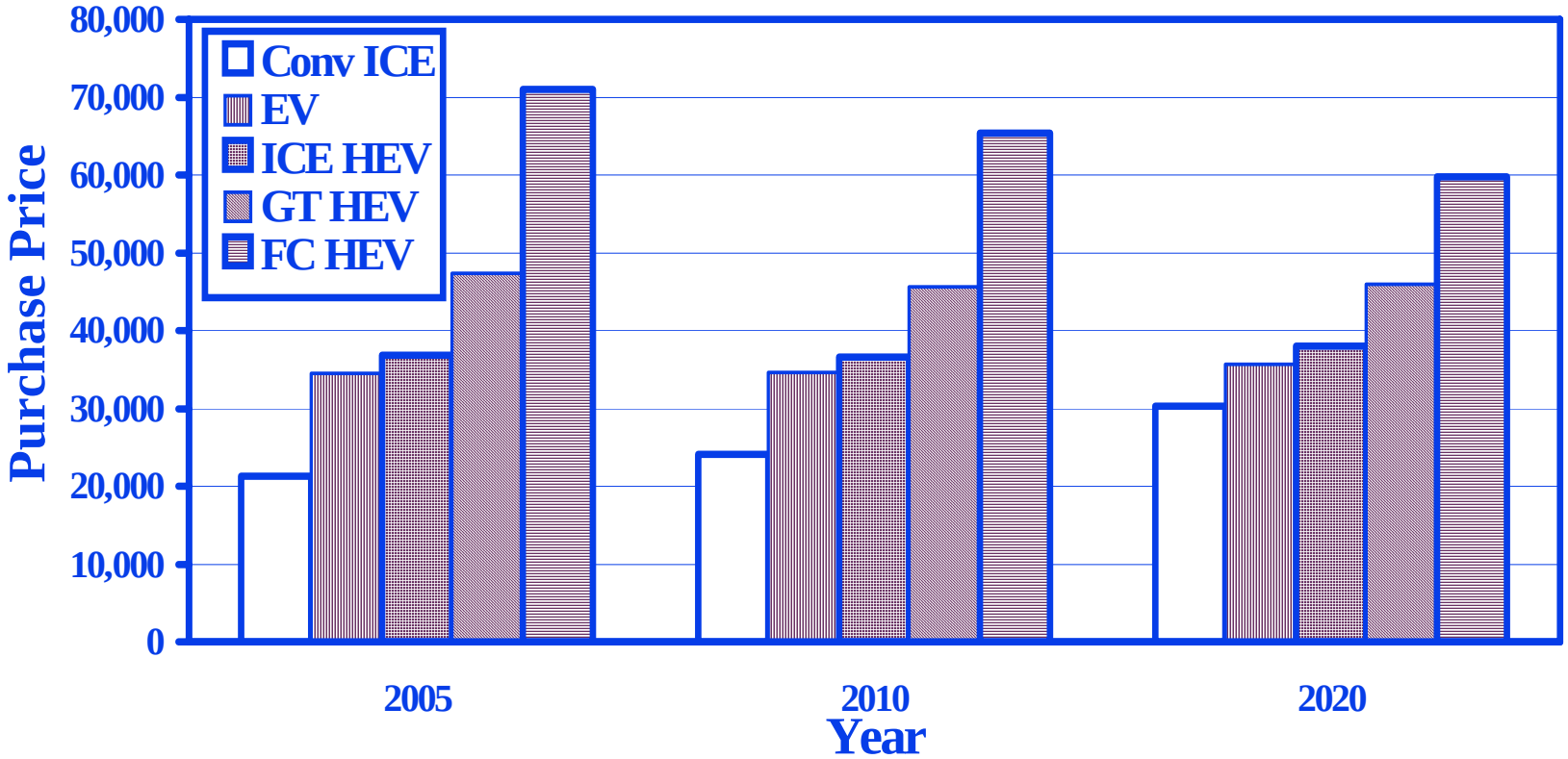


Projected Electric Ranges, Miles

Vyas, et al, *Electric and Hybrid Electric Vehicles: A Technology Assessment Based on a Two-Stage Delphi Study,* Argonne National Laboratory Report ANL/ESD-36 (Dec. 1997).

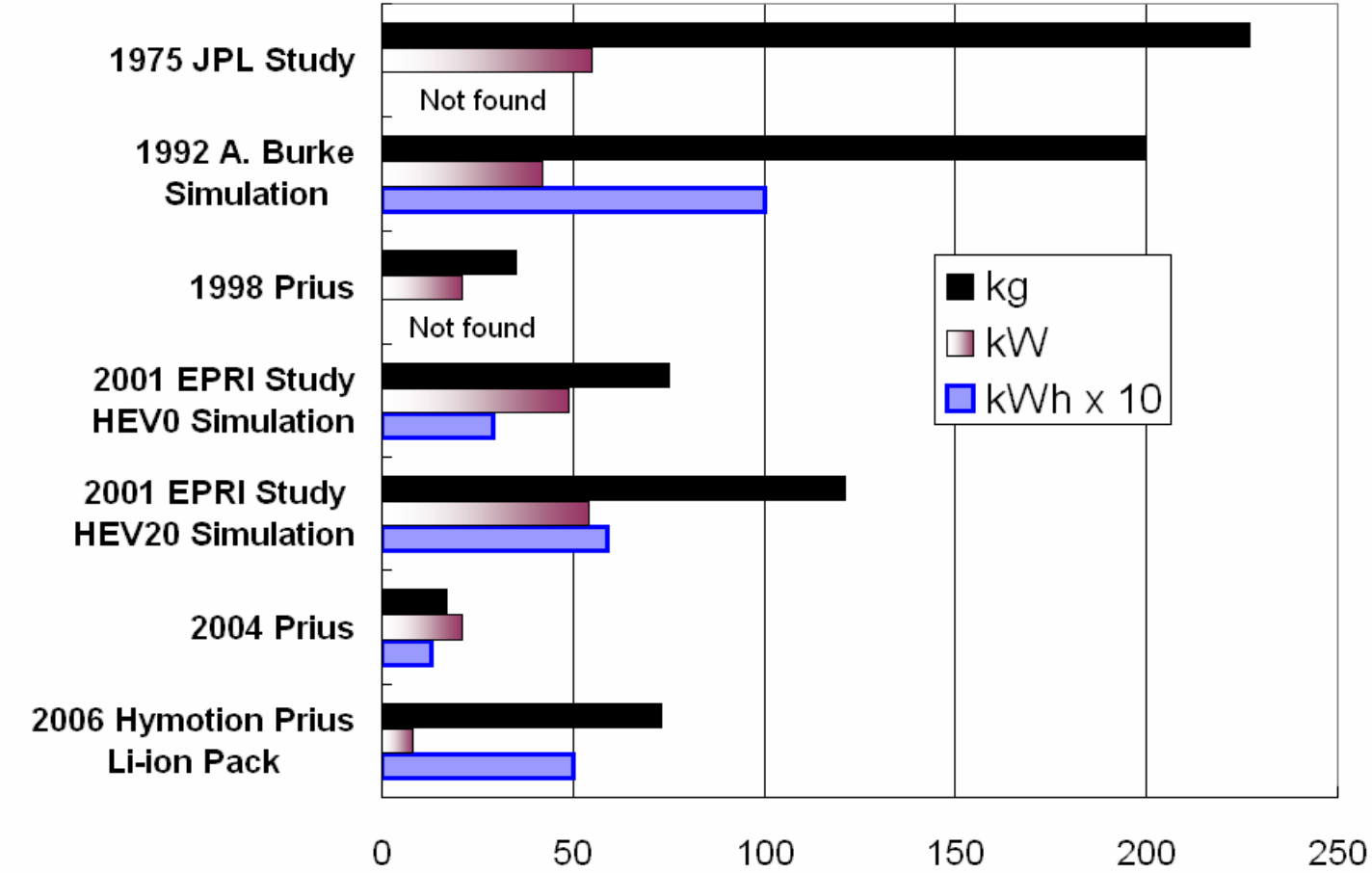
Mid- 1990s Delphi Respondents Predicted HEVs Would Cost More than EVs

Mean Purchase Price By Year



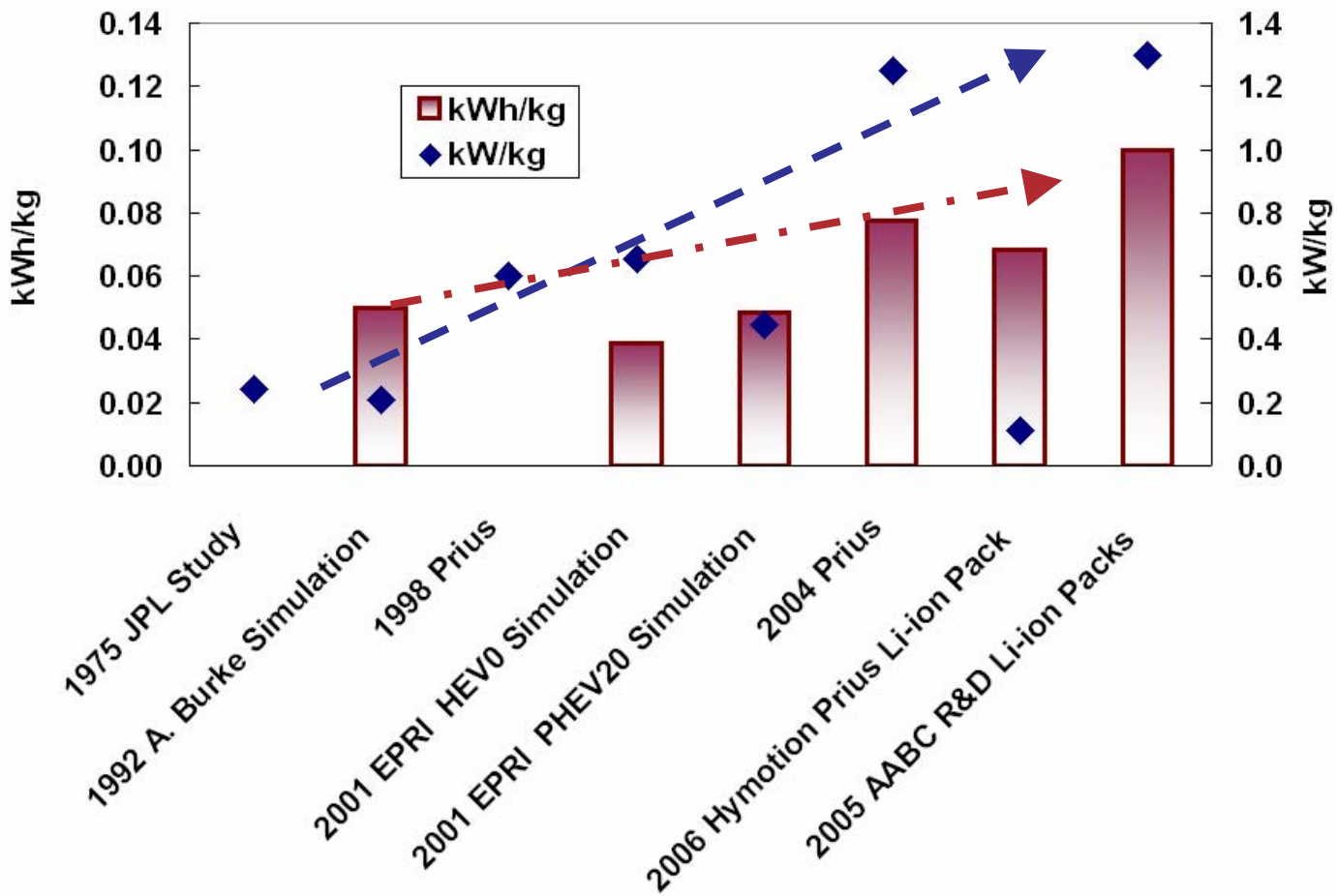
Vyas, et al, *Electric and Hybrid Electric Vehicles: A Technology Assessment Based on a Two-Stage Delphi Study,* Argonne National Laboratory Report ANL/ESD-36 (Dec. 1997).

Compared to Past Theoretical or Experimental Hybrids, Prius Reduces Cost by Getting Most From the Least Battery Pack

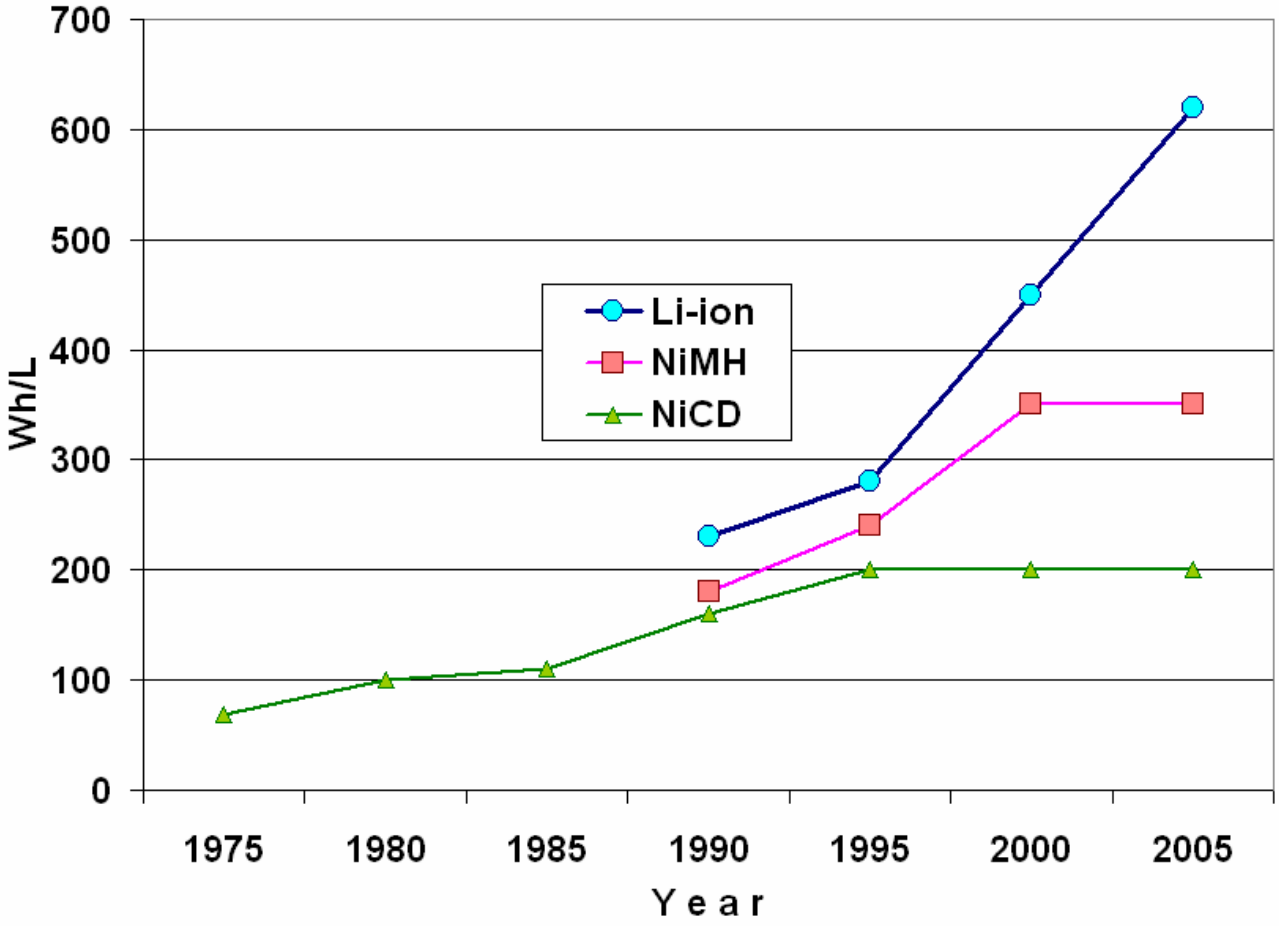


Battery Pack Attributes in Selected HEVs Simulated, Built, or Tested over the Years

The "Breakthrough" to Date in HEV Batteries Seems to Be in Power Density, Not Gravimetric Energy Density



For the PHEV, the Key Additional Breakthrough Appears to be Li-ion Volumetric Energy Density



Conclusions

Evolution of Batteries, Motors and Engines Slowly led to Today's Compact, Efficient Parallel Hybrid Powertrains. Continuation of Established Trends, Adapting Parallel HEVs and Using Small Batteries Matched to Minimum Cost, Off-Peak Charging Time Periods and to Existing kW Throughput Capabilities of Residences with Garages, will Lead to the Initial Wave of Successful PHEV Powertrains.