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How Will Light Duty Plug-in Hybrid Vehicle Electric Drive Emerge and Evolve? An Examination of Recent and Current Developments.

Danilo J. Santini, Senior Economist

Center for Transportation Research

Argonne National Laboratory

Research sponsors:

Ed Wall, Program Manager, OFCVT, DOE

Tien Duong, Team Leader, Vehicle Technologies, OFCVT, DOE

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2001 Studies By Argonne, EPRI & Others Evaluated Cost Effectiveness of Degrees of Electric Drive

Charge-sustaining Hybrids

Minimal hybrid = idle off, perhaps some degree of regenerative braking (ISG), no grid connection

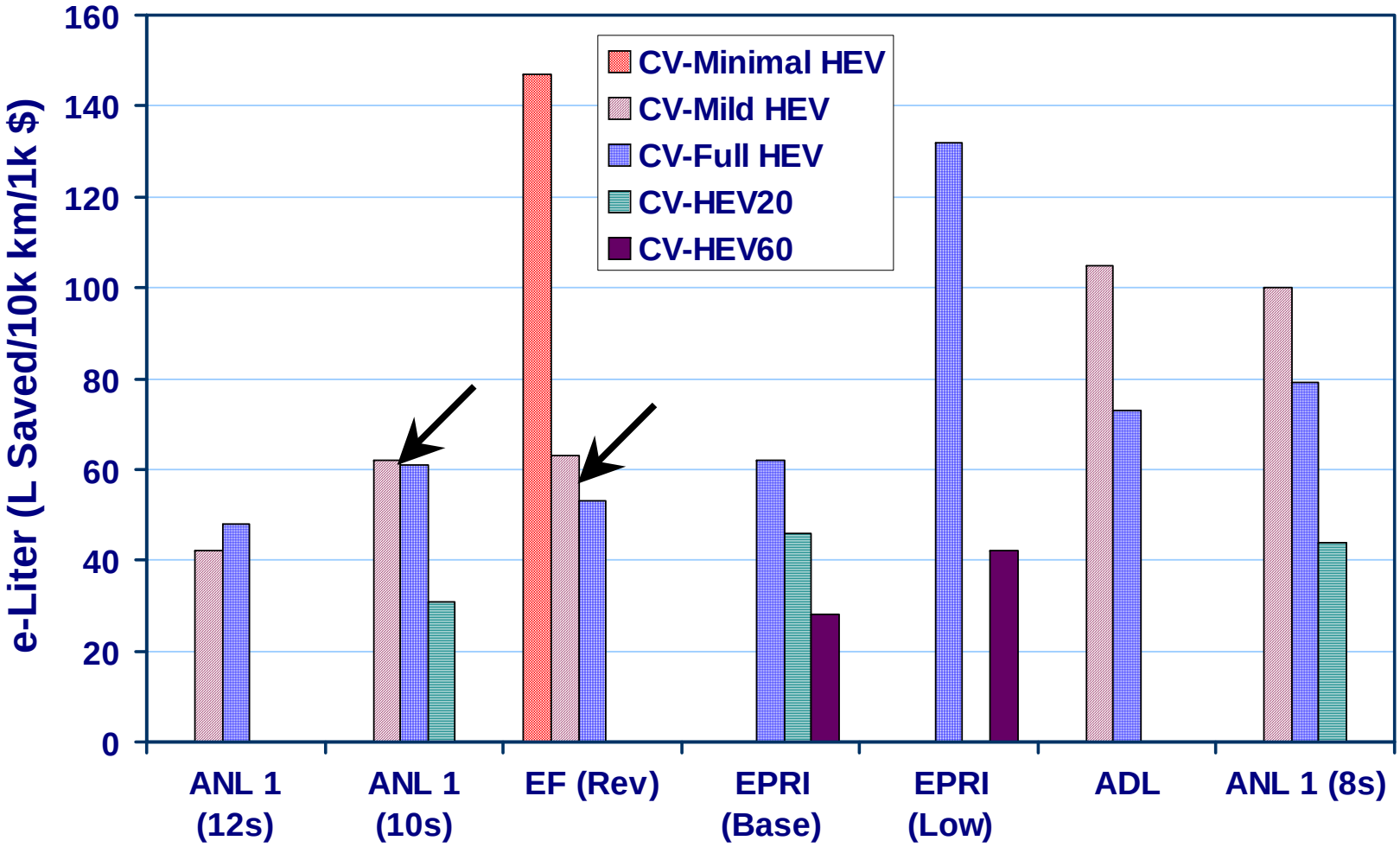
Mild hybrid = between minimal (or nothing) and full, in any given study, no grid connection

Full hybrid = idle off, considerable regenerative braking, electric launch, no grid connection

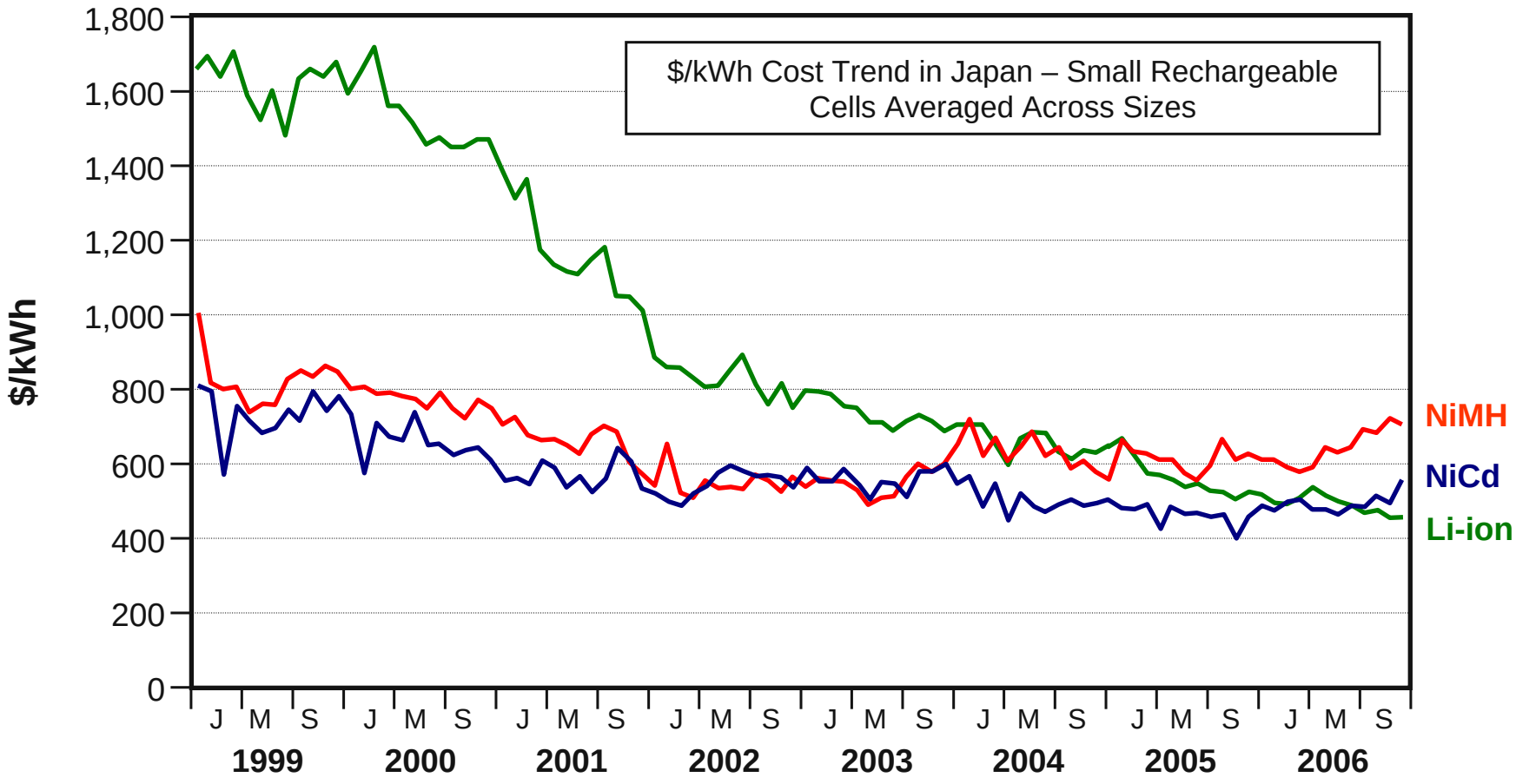
Charge-depleting (and sustaining) Hybrids

HEV## = a grid connectable hybrid with ## miles of electric range

Cost Effectiveness Implied that "Minimal HEVs" Were Most Desirable, Mild and Full HEVs Were Close to One Another, and PHEV Options Were Relatively Ineffective



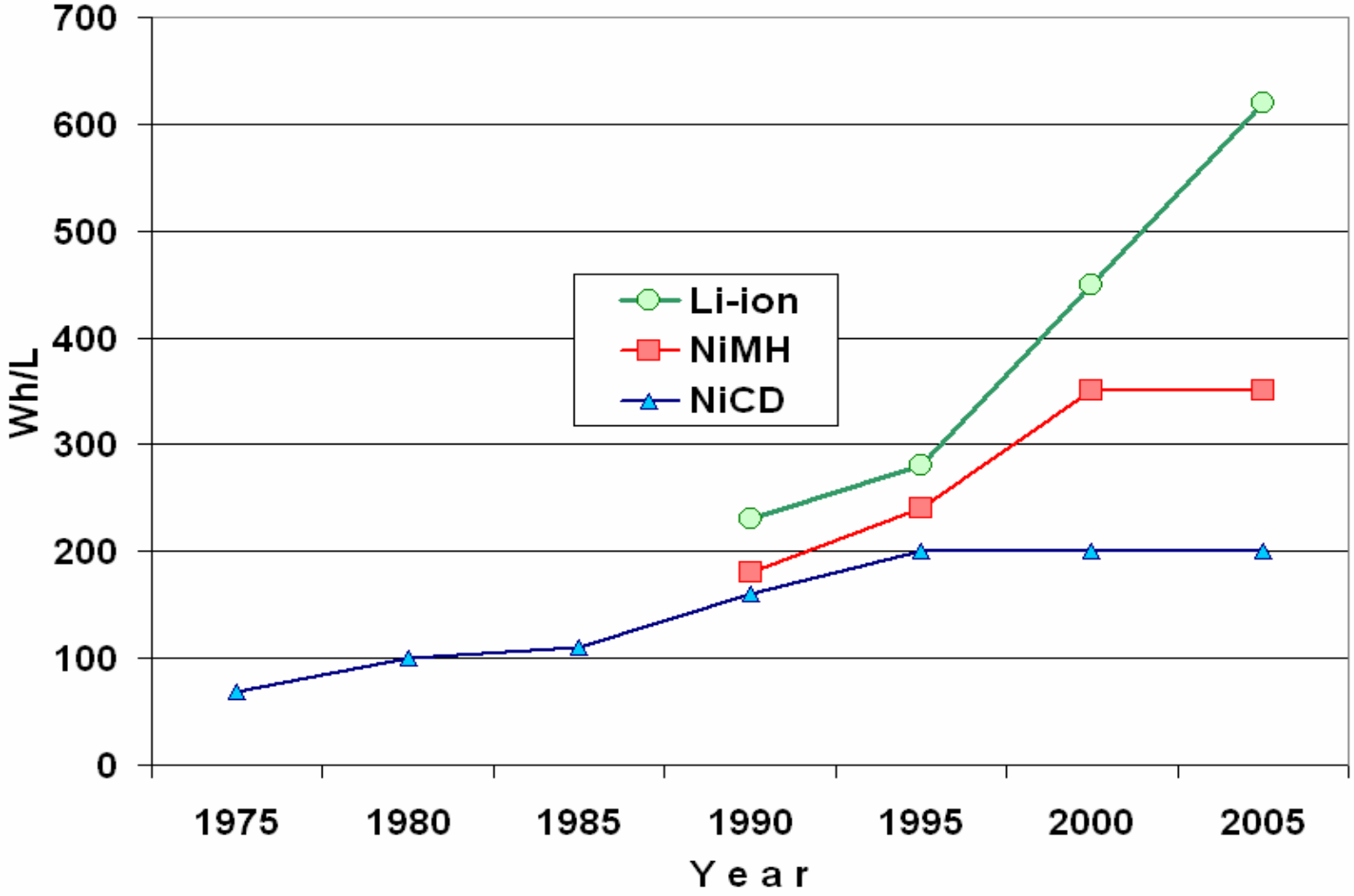
Since 2001, Things Have Changed. NiMH Batteries, Assumed Then, Increased in Cost, Li-ion Dropped



Source: TIAX, based on METI data

Japanese records of cost of batteries for *consumer electronics*

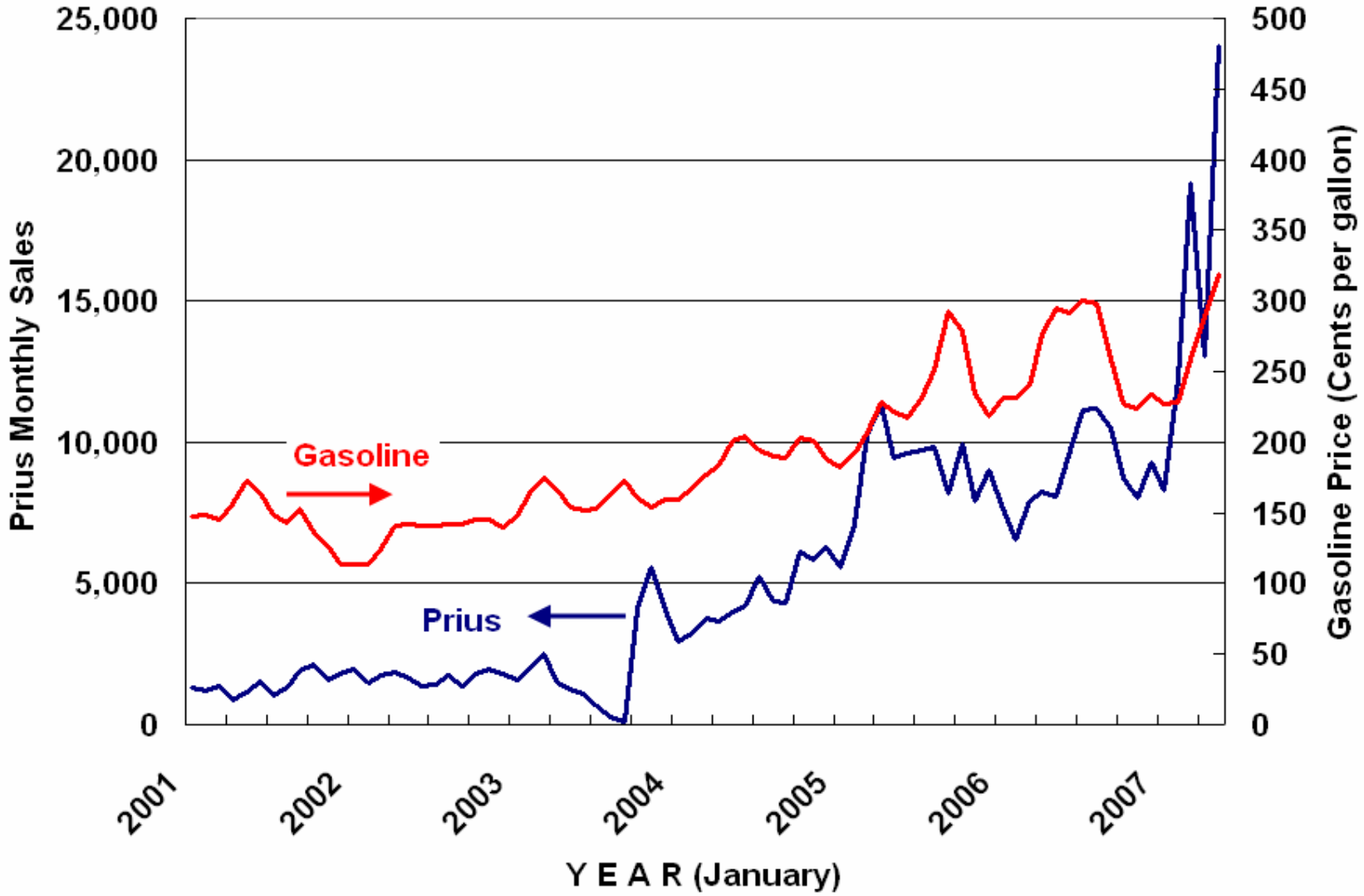
Energy Density of Li-ion Batteries Has Increased Dramatically Since Introduction in Consumer Electronics



Japanese records of Wh/L of batteries for *consumer electronics*

Source: Shinsuke Ito, EVS-22 Plug-in Hybrid Electric Vehicle Workshop

Since 2001, Gasoline Prices Have Increased, A New Prius Full Hybrid System Was Introduced, and Prius Sales Surged

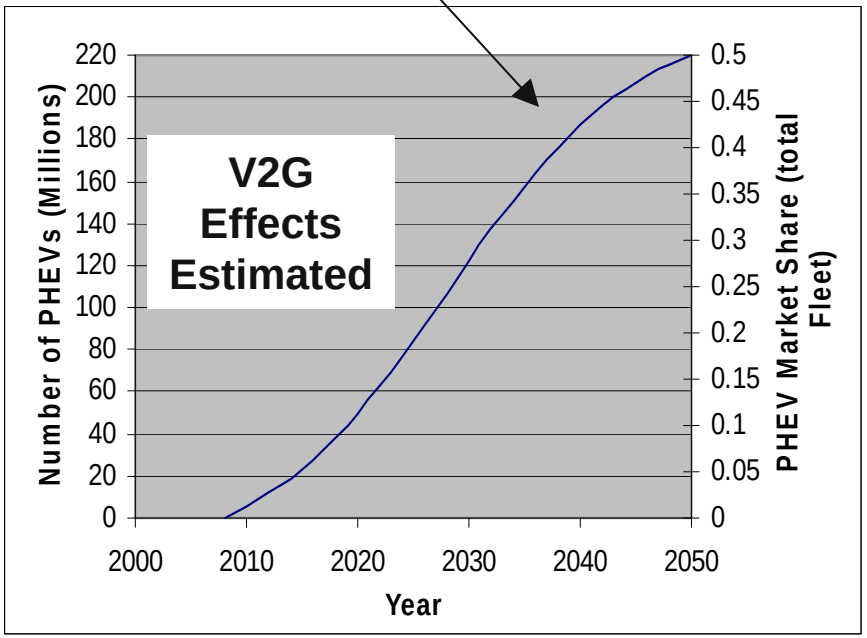


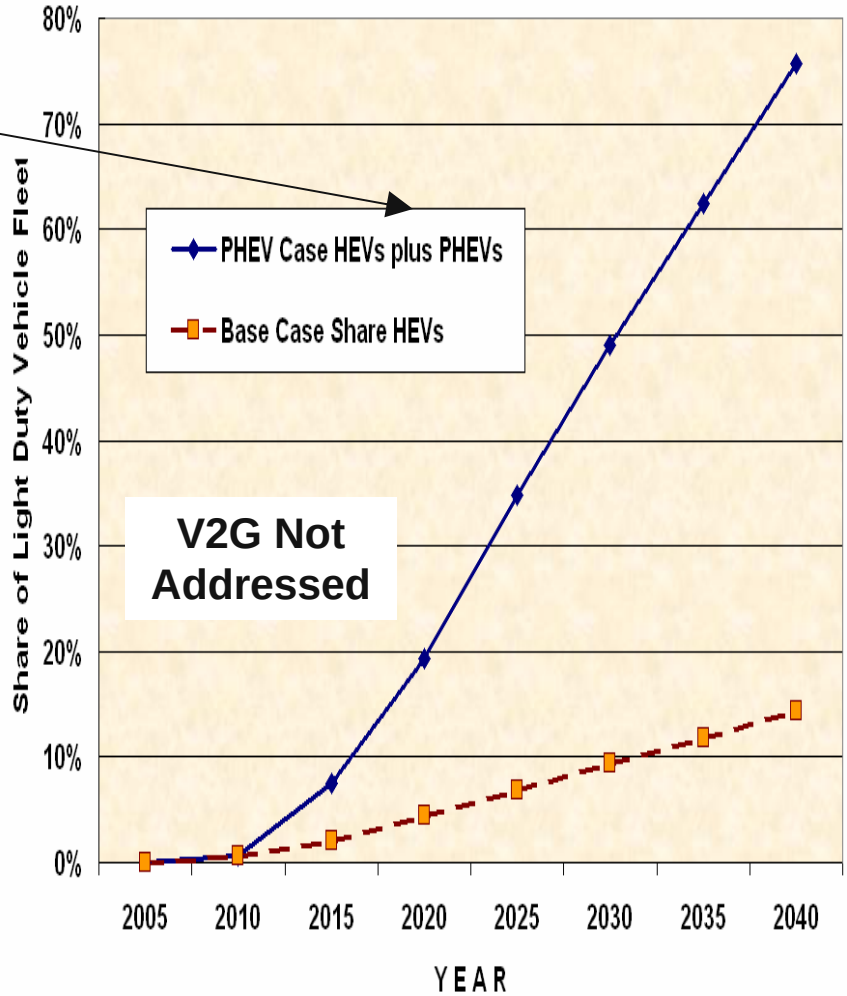
EPRI's '01 Study of PHEV20s & PHEV60s Caused Some Analysts to Assess Long-Term Cases With Many PHEVs

"What If" scenarios

AMIGA Scenario by Argonne

WinDS Scenario by NREL





Courtesy of W. Short, NREL

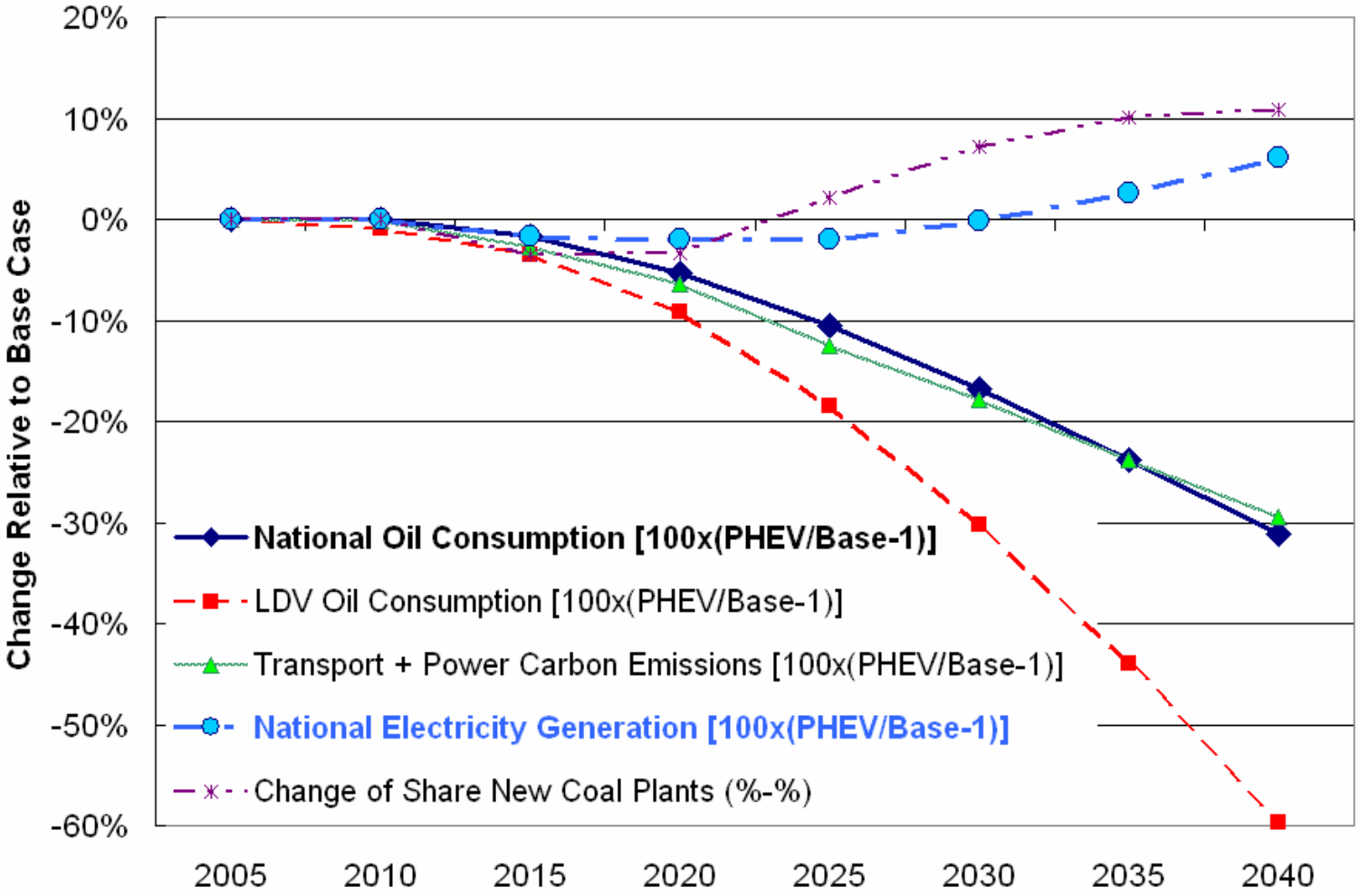
Courtesy of D. Hanson, Argonne

Massive Success Requires Only a Few Percent Increase in Total Generation, Might Lead to Significant Use of Wind Power

2050 Projected Values	Base Case (no PHEVs)	PHEV-20 Case	PHEV-60 Case
Gasoline use (Billions of Gallons)	368	255 (31% decrease)	212 (43% decrease)
Wind Generation (TWh/year)	757	853 (13% increase)	1554 (105% increase)
Total Load (TWh/year)	9392	9808 (4.4% increase due to PHEV load)	10082 (7.3% increase due to PHEV load)
Increase of Wind Electricity vs. Base Case	-	0.6%	7.5%
Total Installed Generation Capacity (GW)	2161	2092	1972
Generation from Coal (TWh/year)	8272	8597 (3.9% increase)	8169 (1% decrease)
Electric and Light Duty Transport Sector CO2 (Million Tons CO2/year)	10956	9910 (9.5% decrease)	9346 (14.7% decrease)

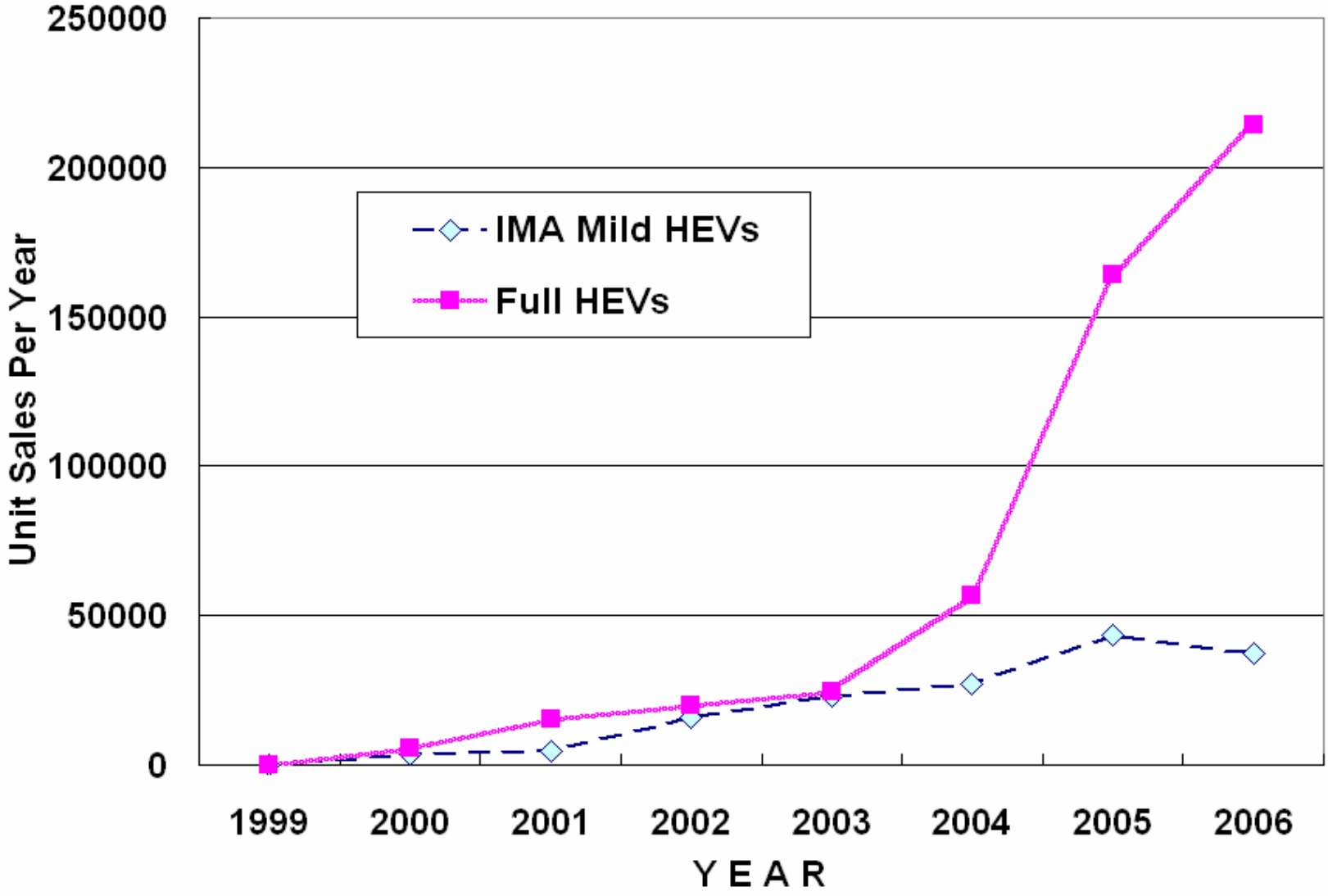
See Short and Denholm, NREL/TP-620-39729, April 2006

Analysts Using the AMIGA Model also Predicted Significant Increases in Wind Generation, Little Change in Total Generation, Potentially Large Light Duty Vehicle Oil Use Cuts

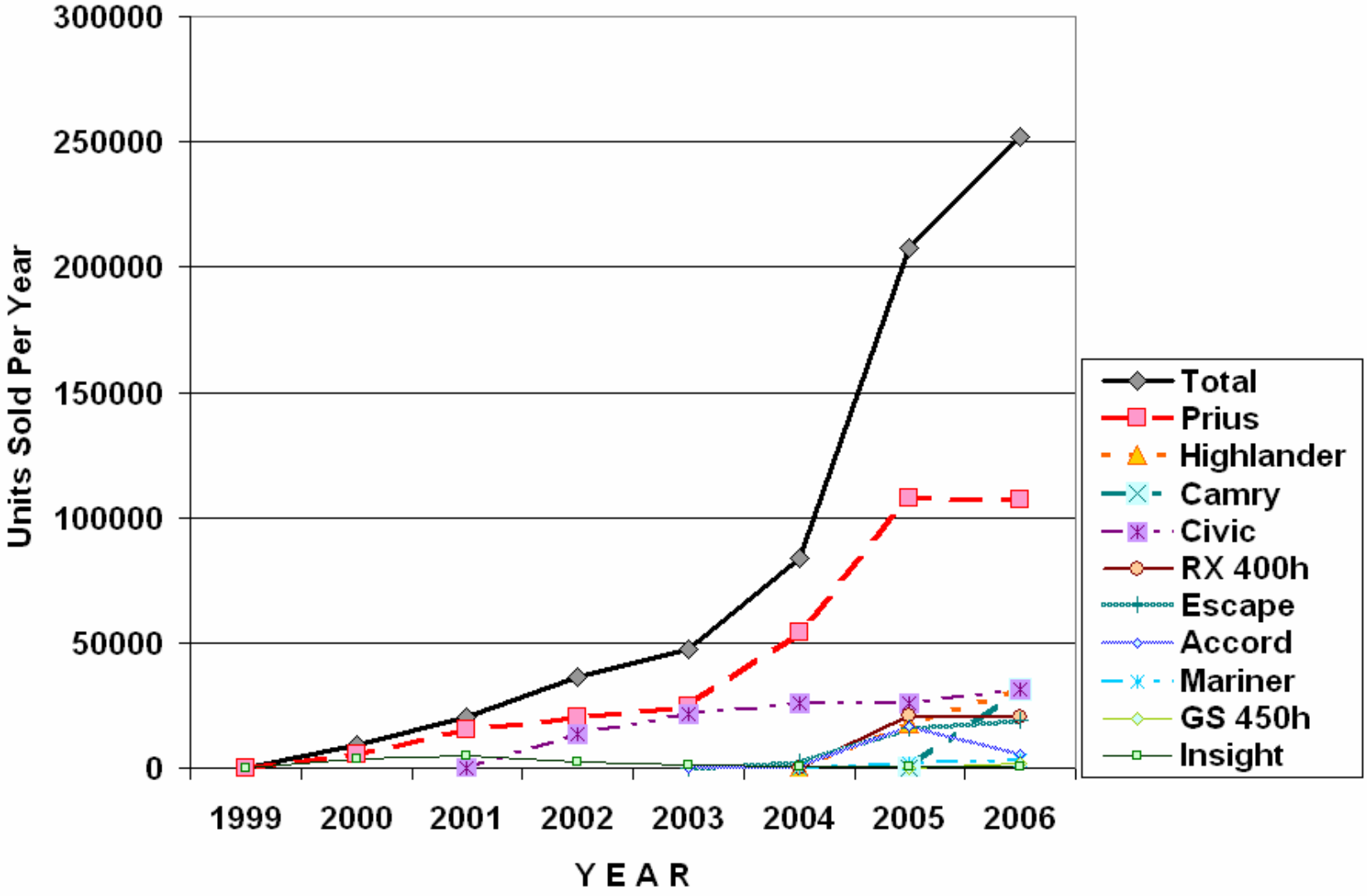


Source: P. Balash* et al: Use of Hydrogen for the Light Duty Transportation Fleet: Technology and Economic Analysis. Run data provided by D. Hanson, Argonne National Lab
* National Energy Technology Laboratory

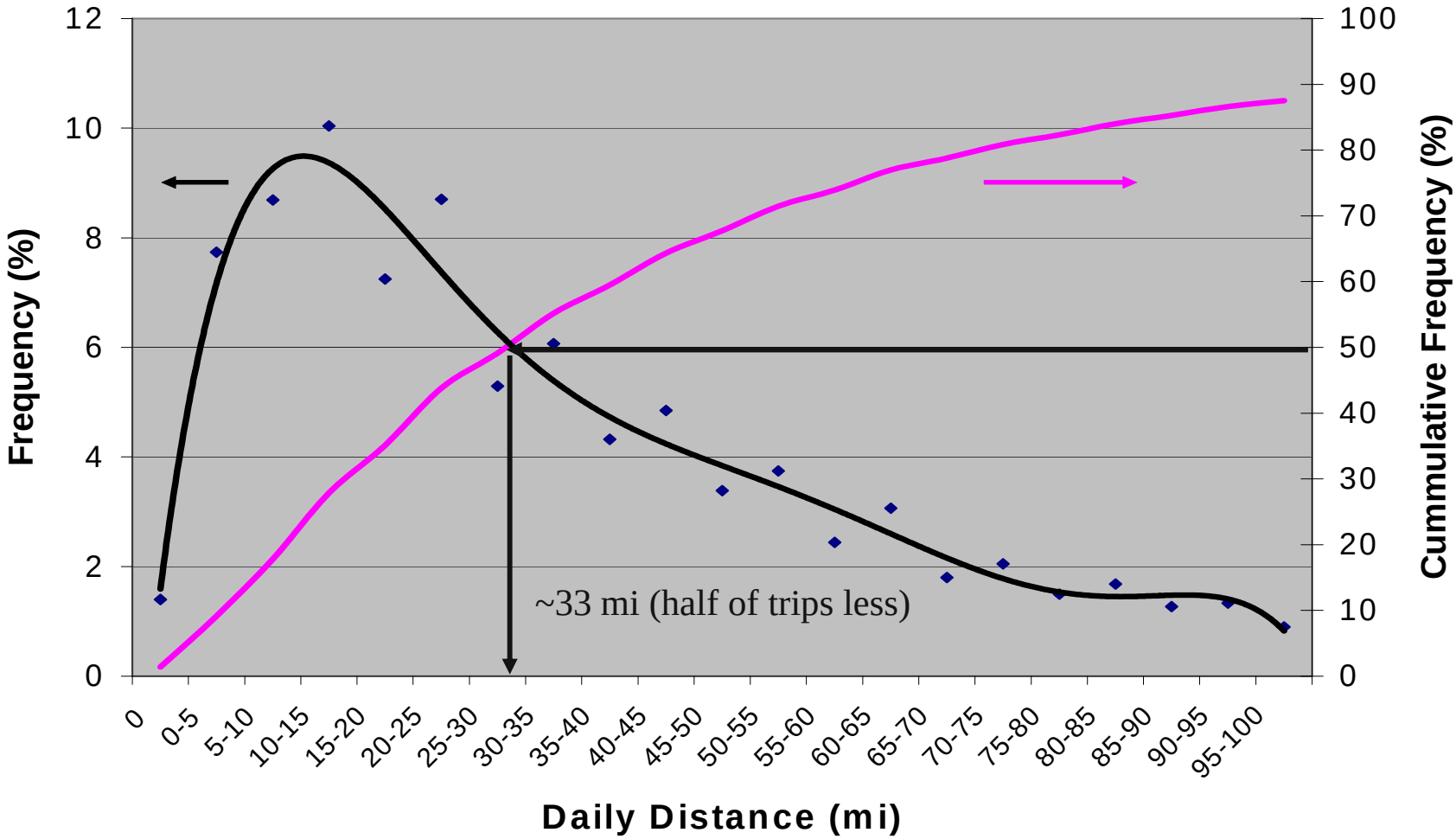
Despite 2001 Cost Effectiveness Estimates, the Full Hybrid is Capturing the Market, Not Minimal or Mild Hybrids



The Prius, Which is Both a Full Hybrid (w Toyota THS System) and a Unique Dedicated HEV, Leads HEV Sales



PHEV Analysts Noted that a Modest Amount of EV Range Can Substitute Electricity for a Lot of Gasoline Miles



Source: 1995 National Personal Transportation Survey

If a PHEV is Charged Every Day, Even the Out of Town Trips Will Use Some Electricity and Contribute to Oil Savings

Daily Travel Range of Vehicle	VMT Share in NHTS 2001	PHEV TYPE		
		PHEV 10	PHEV 20	PHEV 60
		Max % VMT by Electricity	Max % VMT by Electricity	Max % VMT by Electricity
Up to 10 Miles	3.3%	3.3%	3.3%	3.3%
10.01-20 Miles	8.1%	5.3%	8.1%	8.1%
20.01-60 Miles	36.8%	10.1%	20.2%	36.8%
Over 60 Miles	51.8%	4.5%	8.9%	26.7%
Sum	100.0%	23.2%	40.6%	74.9%

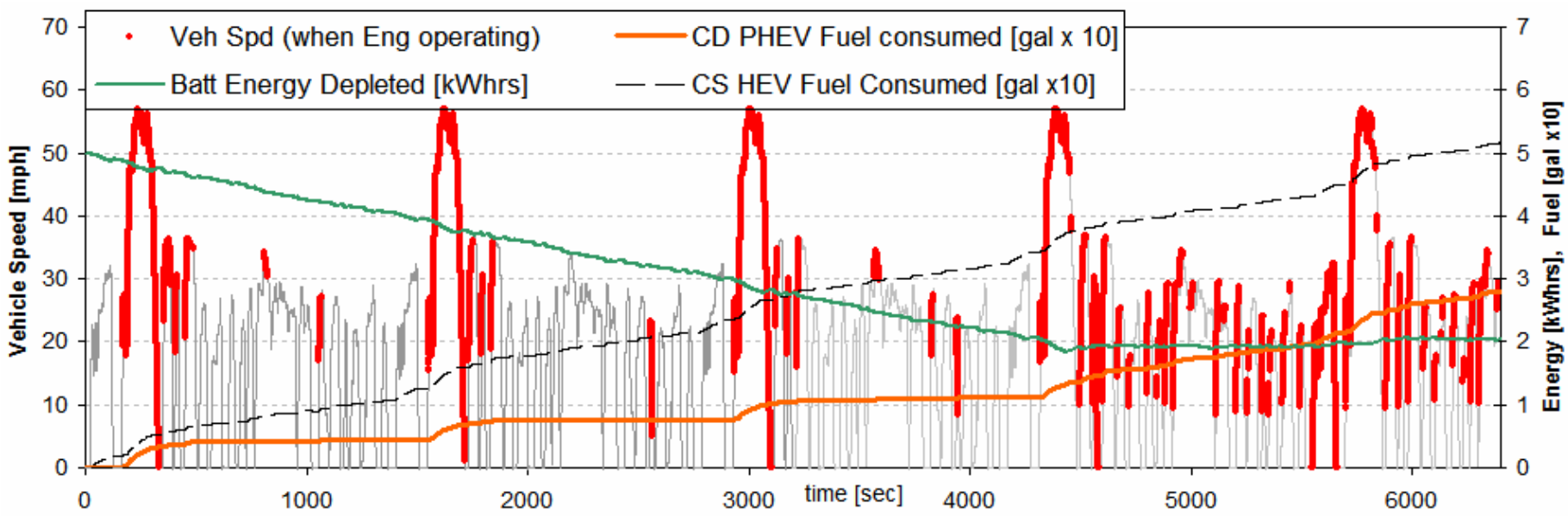
Assumes one charge per day, 100% market penetration of the specified PHEV technology, and all electric drive until battery depletion (not blended charge depletion). Blended charge depletion requires more miles to use a given amount of kWh from the grid.

A Limited "EV Option" for the Japanese and European Prius (Hidden in U.S.) Allowed Introductions of "Modest" PHEV Conversion Kits Now, Using Li-ion Packs

Hymotion Plug-in Prius Testing at Argonne National Laboratory

This is not a PHEV as Simulated in 2001 Studies: Engine and Electric Machine "Blend" Power Together

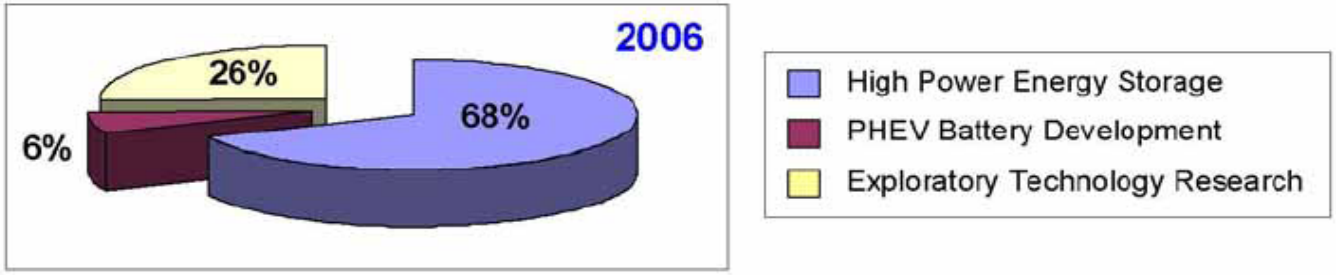
Hymotion PHEV Tests –Repeat UDDS Cycles



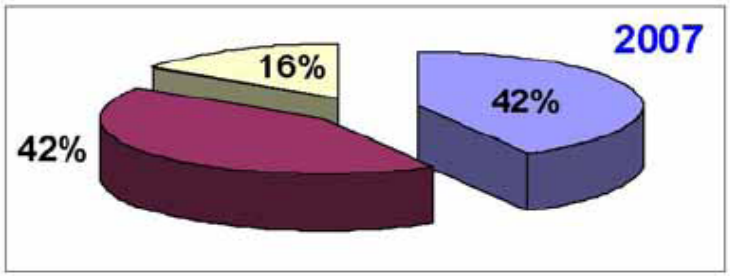
- Charge depletion operation into the 4th UDDS (approx 25 miles)
- Displaced more than half of the gasoline vs. a conventional Prius test during depletion
- Recharged in about 5 hours

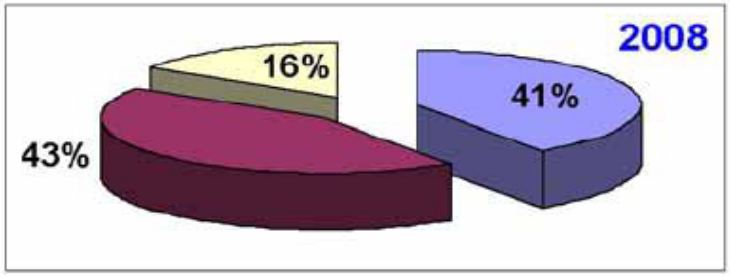
Source: M. Duoba & APTF, Argonne

Emerging Optimism Has Led to an Expansion of DOE R&D Funding for PHEV Battery Development



FY	Budget
2006	$24.442 Million
2007	$40.912 Million
2008*	$41.805 Million
	*Presidential request





Source: D. Howell. Electrical Energy Storage: Plug-in Hybrid Electric Vehicle Battery Research and Development Activities. DOE PHEV Stakeholders Meeting, June 13, 2007

M. Anderman Recently Argued that an All-Electric PHEV Option for the Camry Would be Problematic

Item (Toyota Camry Glider)	Unit	Full HEV†	Blended 32km	AER 16km	Blended 64km	AER 32km
Maximum Power	kW	25	25	140	40	140
Power/energy Ratio	h^{-1}	14	4	23	3	12
Battery Energy	kWh	1.6	6.0	6.0	12.0	12.0
Modules Energy Density	Wh/L	85	130	75	130	85
Battery Pack Energy Density	Wh/L	43	78	45	78	51
Battery Pack Volume	L	38	77	133	154	235
Cargo Space Loss	L	48	96	167	192	294
Hybrid Cargo Space	L	300	252	181	156	54
Hybrid Cargo Space Ratio	%	73	61	44	38	13
Conv. Camry Cargo Space	L	410				

† NiMH battery. All others refer to Li-on battery.

Source: M. Anderman, AABC 2007, Long Beach CA

GM Announced Plans For Two PHEV Powertrains, A Modest One as an Option, & A High Power, All-New PHEV, the VOLT

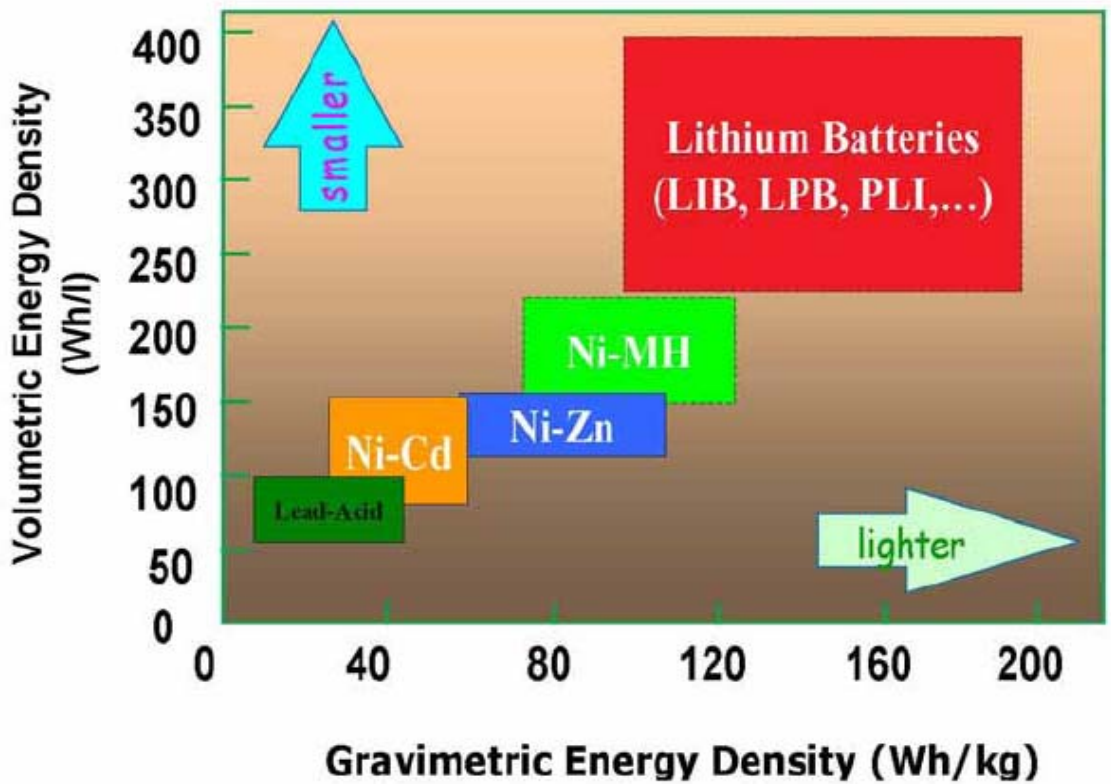
- **Two-Mode Full Size SUV Hybrid**
  - **EV Range:** Only at low speeds and loads
  - **Recharge:** Only while driving
  - **Power:** For EV mode at low speed in city only
  - **Life:** 10 years / 240,000 km

- **Two-Mode Saturn VUE Plug-In Hybrid**
  - **EV Range:** >=16 km all-electric in city
  - **Recharge:** While driving and through plug
  - **Power:** For EV mode in city
  - **Life:** 10 years / 240,000 km

- **E-Flex Range Extended EV (Compact Car)**
  - **EV Range:** >=64 km all-electric in city
  - **Recharge:** While driving and through plug
  - **Power:** For EV mode at full performance
  - **Life:** 10 years / 240,000 km

There is Great Hope that Lithium Ion Technology Can Continue to Advance, and Not "Plateau" at Present Levels

- Lithium-ion has higher volumetric and gravimetric energy densities than competing battery technologies, enabling smaller and lighter battery packs.
- Lithium-ion also promises reduced cost, increased performance, and longer life.



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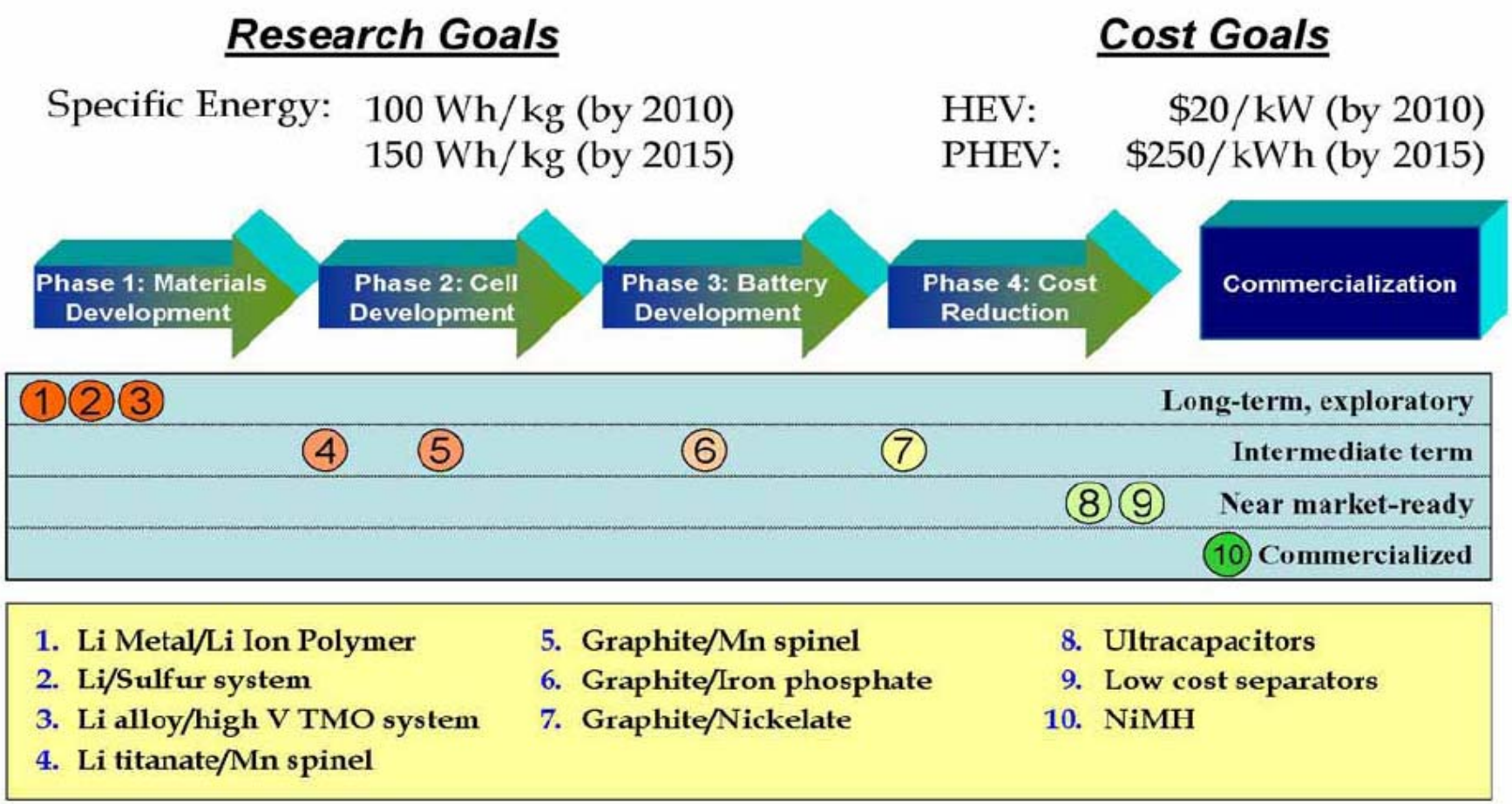
The Energy Storage Program of DOE's Office of FreedomCAR and Vehicle Technologies Sees Potential Merit in Several Li-Ion Battery Chemistries and Improved Supporting Technology



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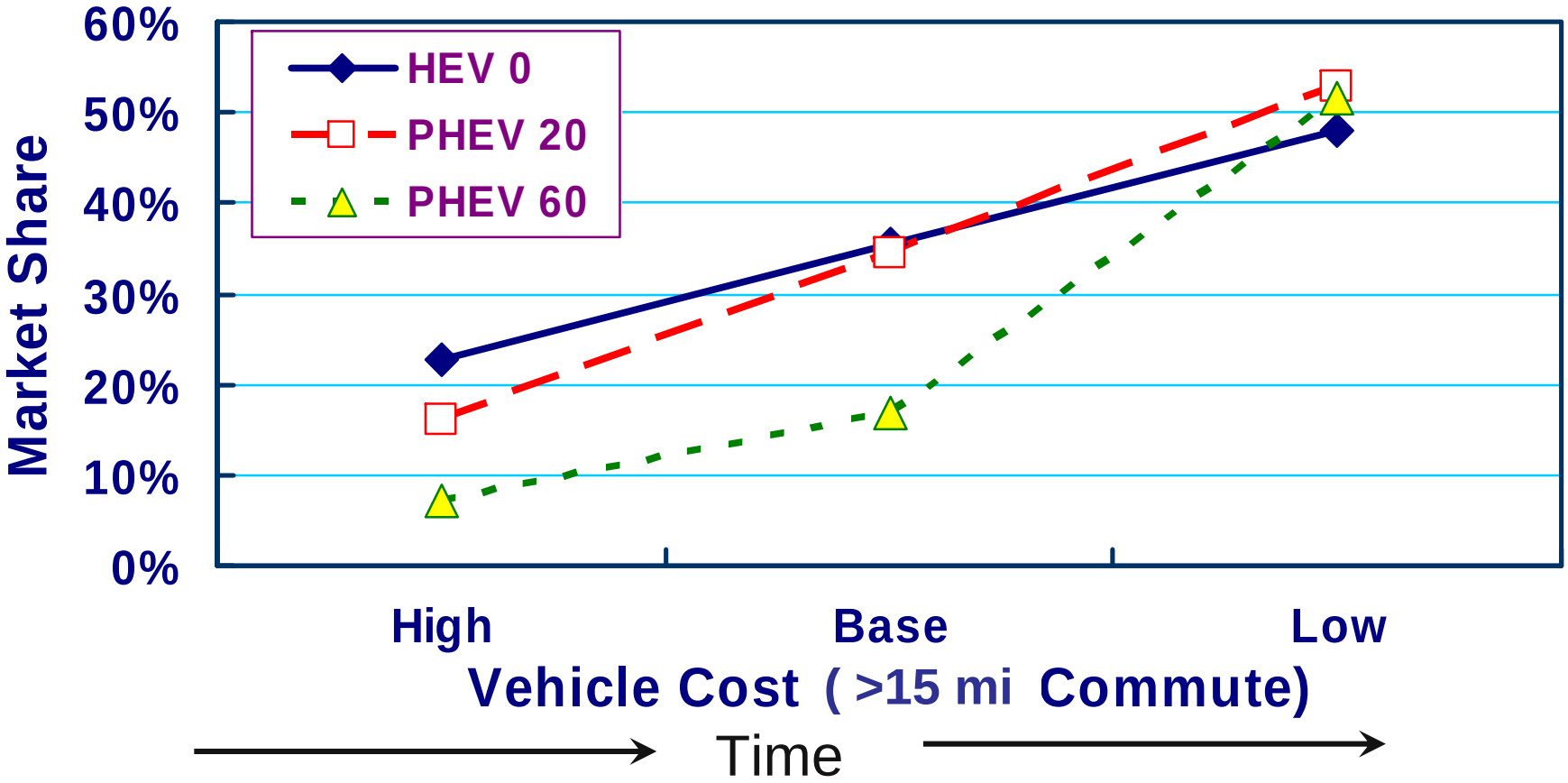
For EPRI's Simulated Parallel Plug-in Hybrids, Less Expensive Batteries Mean Greater Affordability for Electric Range, and Generally Greater Market Success

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



Both Ford and GM See the Possibility of Many Potential Long-Term Paths Based Fundamentally on "More Electric Drive"

Ford press release: media.ford.com

- The Ford Edge with HySeries Drive™ is the world's first drivable fuel cell hybrid electric vehicle with plug-in capability.
- Ford's flexible powertrain architecture enables the use of new fuel and propulsion technologies as they develop without redesigning the vehicle and its control systems.
- The HySeries Drive technology is able to operate using a fuel cell, small gasoline or diesel engine connected to an electric generator to make electricity.

Questions for Another Time

- What are the implications of PHEVs for photovoltaic solar power?
- Will a shift to series electric drive rather than the near-term parallel PHEV drive occur? Under what circumstances?