ELECTRIC DRIVE TRANSPORTATION ASSOCIATION
CONFERENCE & EXPOSITION 2006
NOVEMBER 28-30
WASHINGTON DC
USA
battery hybrid fuel cell

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Two Industry Developments That Justify Optimism About Potential for PHEV Success: (Powertrains and Batteries)

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HEV Technology History: 3 Decades

- **ICE HEV/PHEV Powertrain types:**
  - **Series**
    - **HEV charge sustaining**
    - **PHEV as EV range extender**
  - **Parallel**
    - **HEV charge sustaining**
    - **PHEV charge depleting "blended" mode**
- **Battery Evolution:**
  - **Specific Energy (kWh/kg) vs. Specific Power (kW/kg)**
  - **Energy Density (kWh/liter)** vs. Power Density (kW/l)

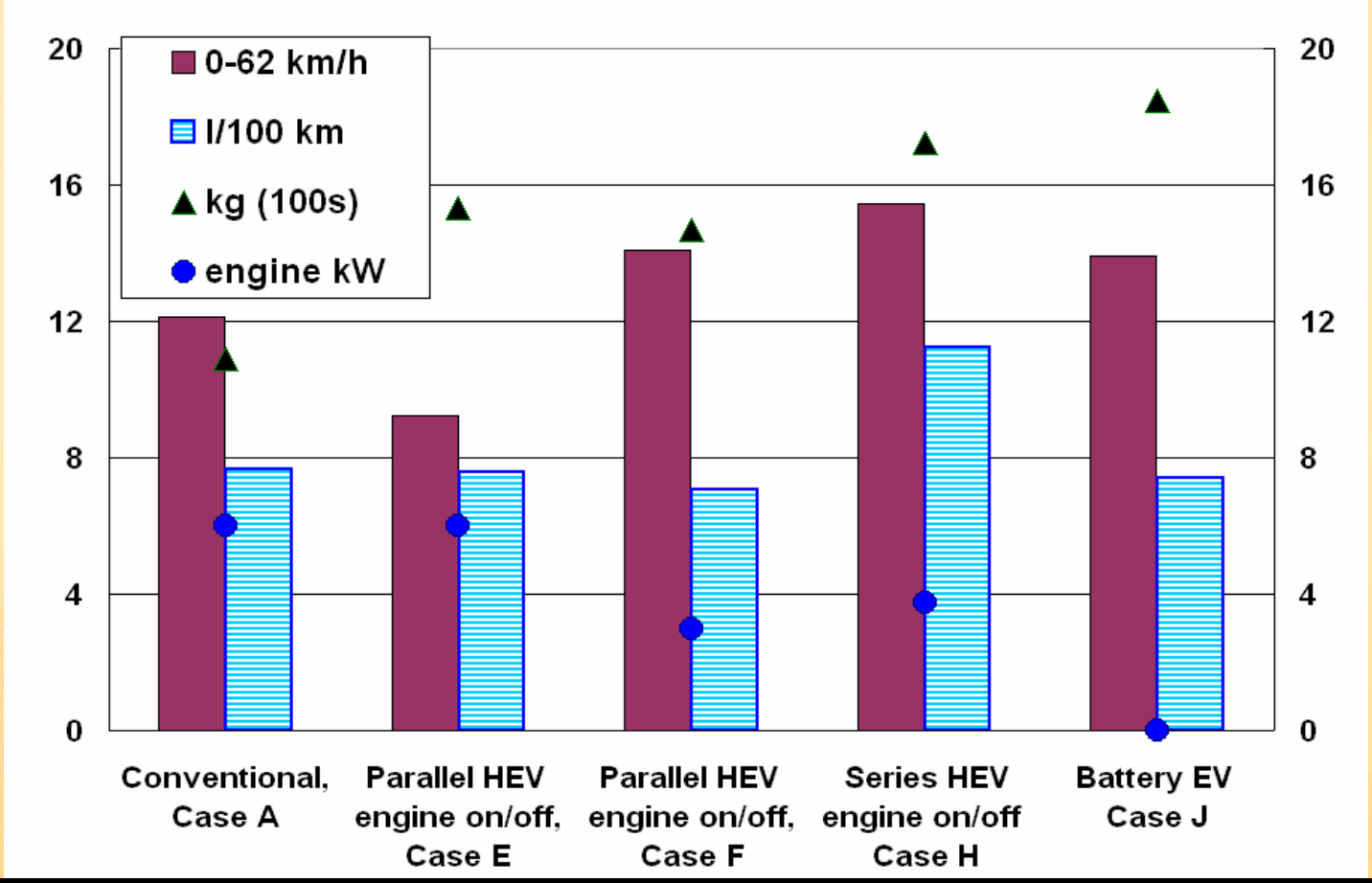
Plug-in Hybrids (PHEVs) Now Possible Because of a Confluence of Events

- Via NiMH chemistry, $/kW dropped sharply (kW/kg rose sharply)
  - (cost per kWh did <u>not</u> drop sharply, however)
- NiMH battery life with narrow SOC swings may be as long as car life
- Superiority of parallel over series ICE hybrids finally became 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 HEVs were successfully marketed, w EV option
- Li-ion battery energy density improved sharply, allowing li-ion battery to “fit” & aftermarket PHEVs to be “easily, cheaply” built

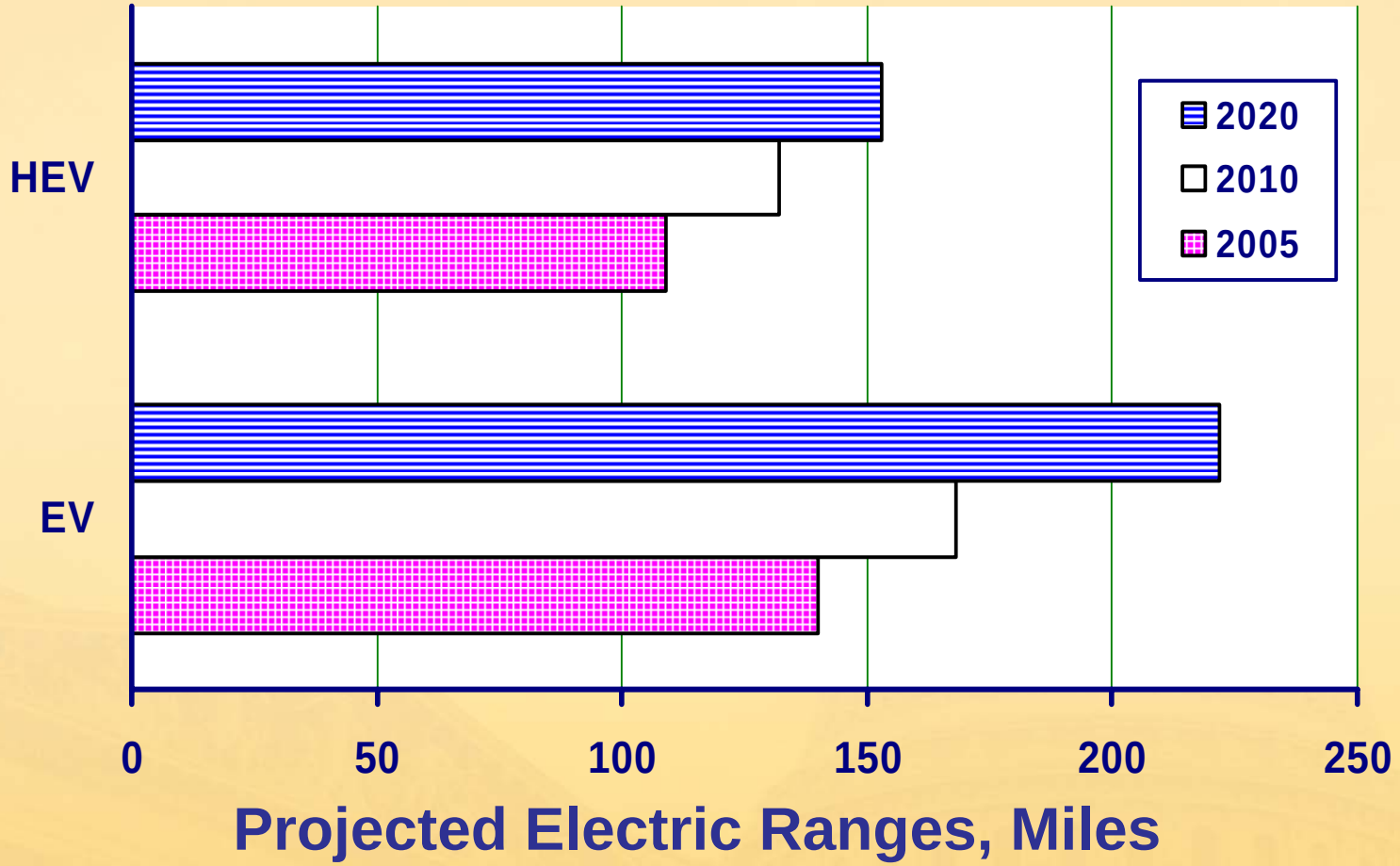
Superiority of the Parallel Powertrain was Predicted, Forgotten, Rediscovered

- **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 Parallel Superiority to Series

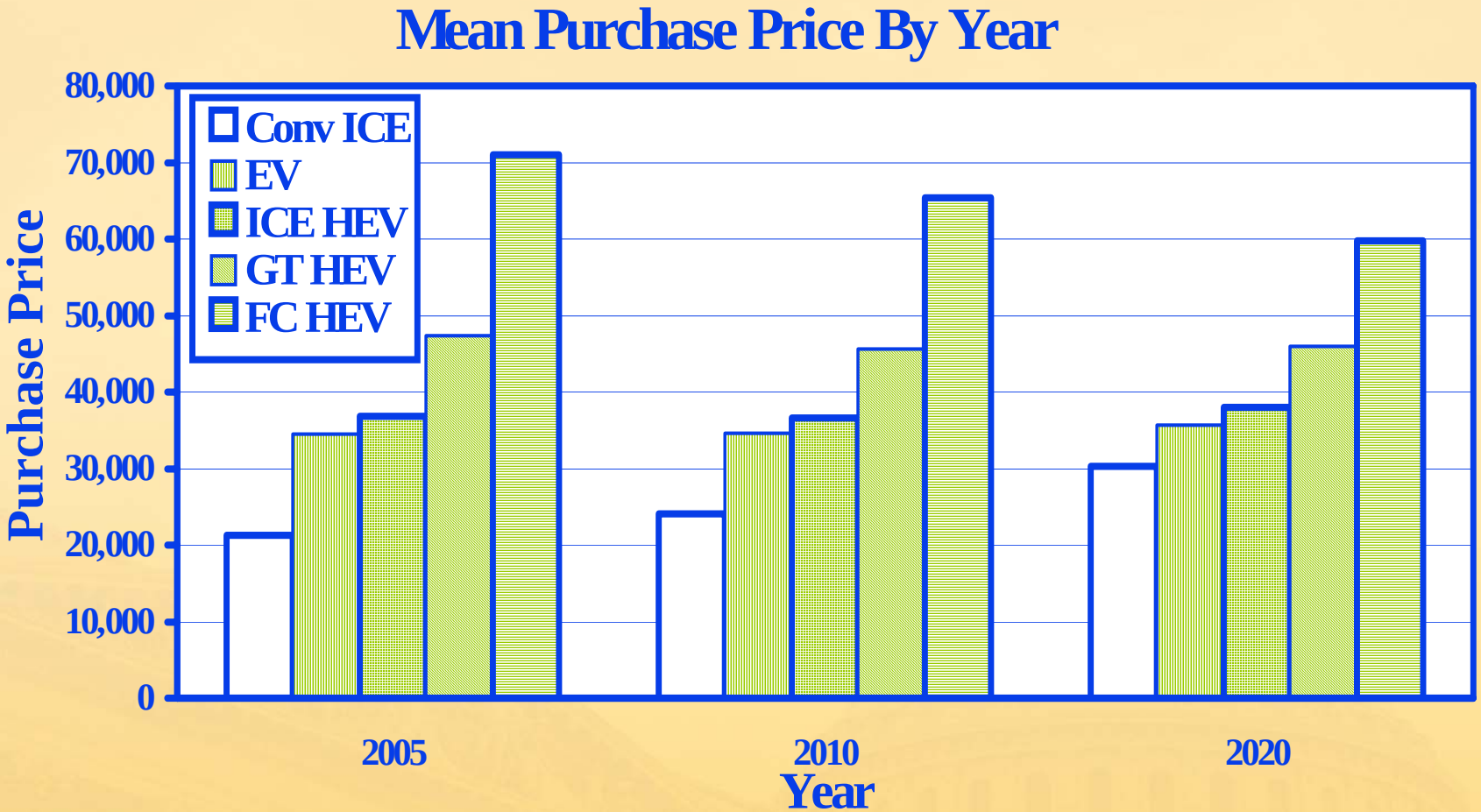


Mid-90s Expectations: Series Range Extender HEVs With Big Batteries, Many EV Mode Miles



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-90s Delphi Respondents Predicted HEVs Would Cost More than EVs



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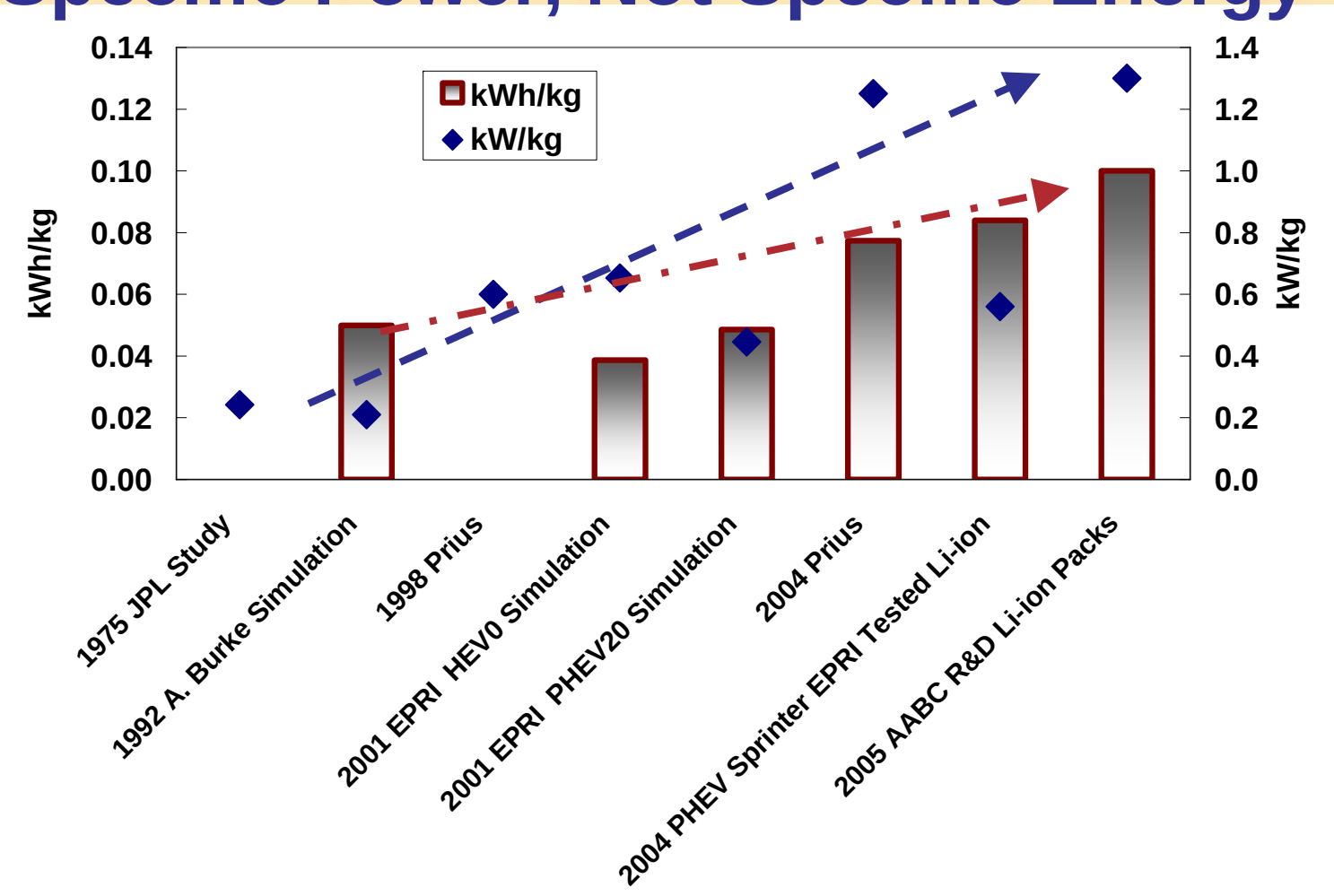
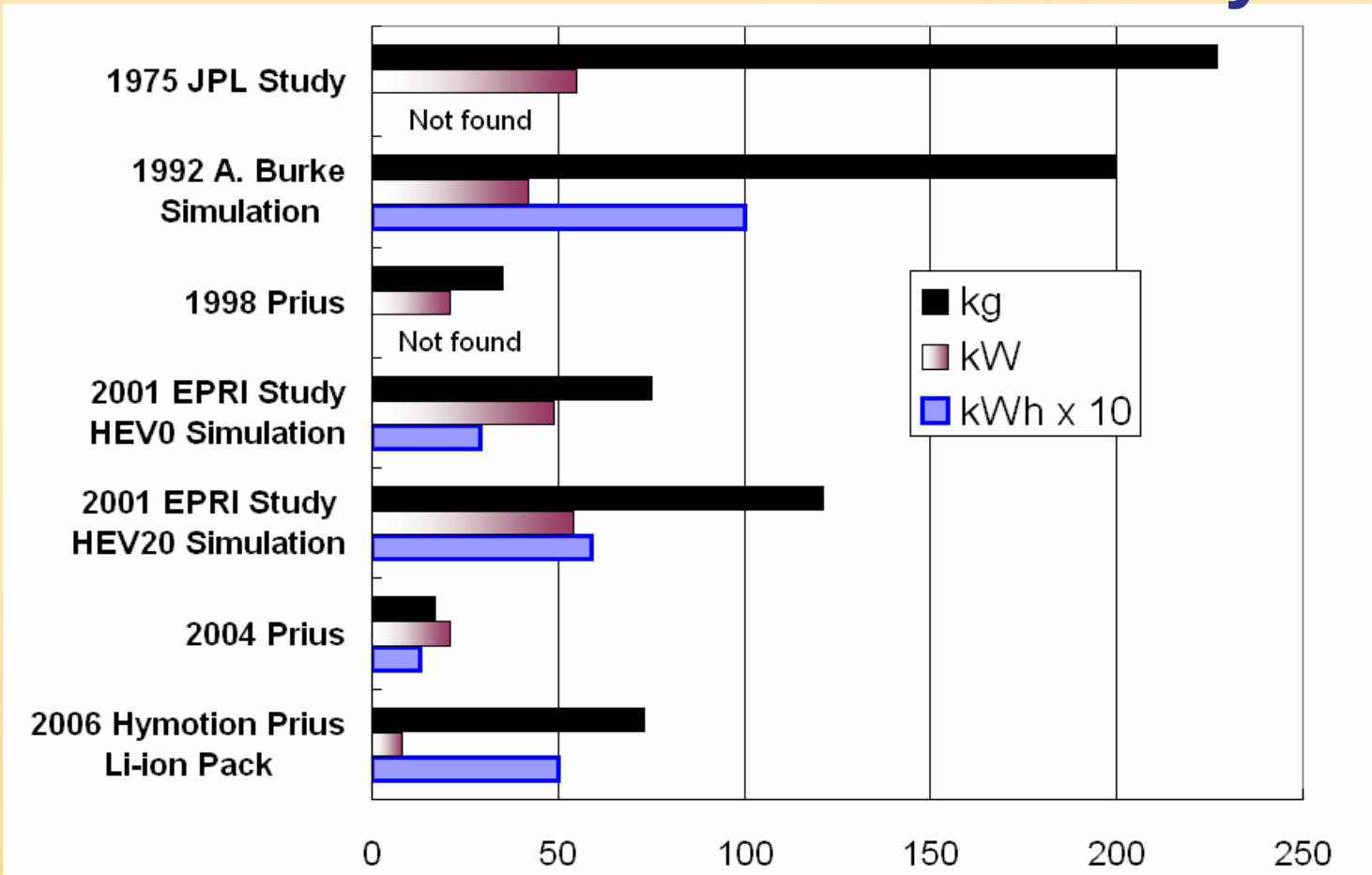
The "Breakthrough" in Batteries has been in Specific Power, Not Specific Energy

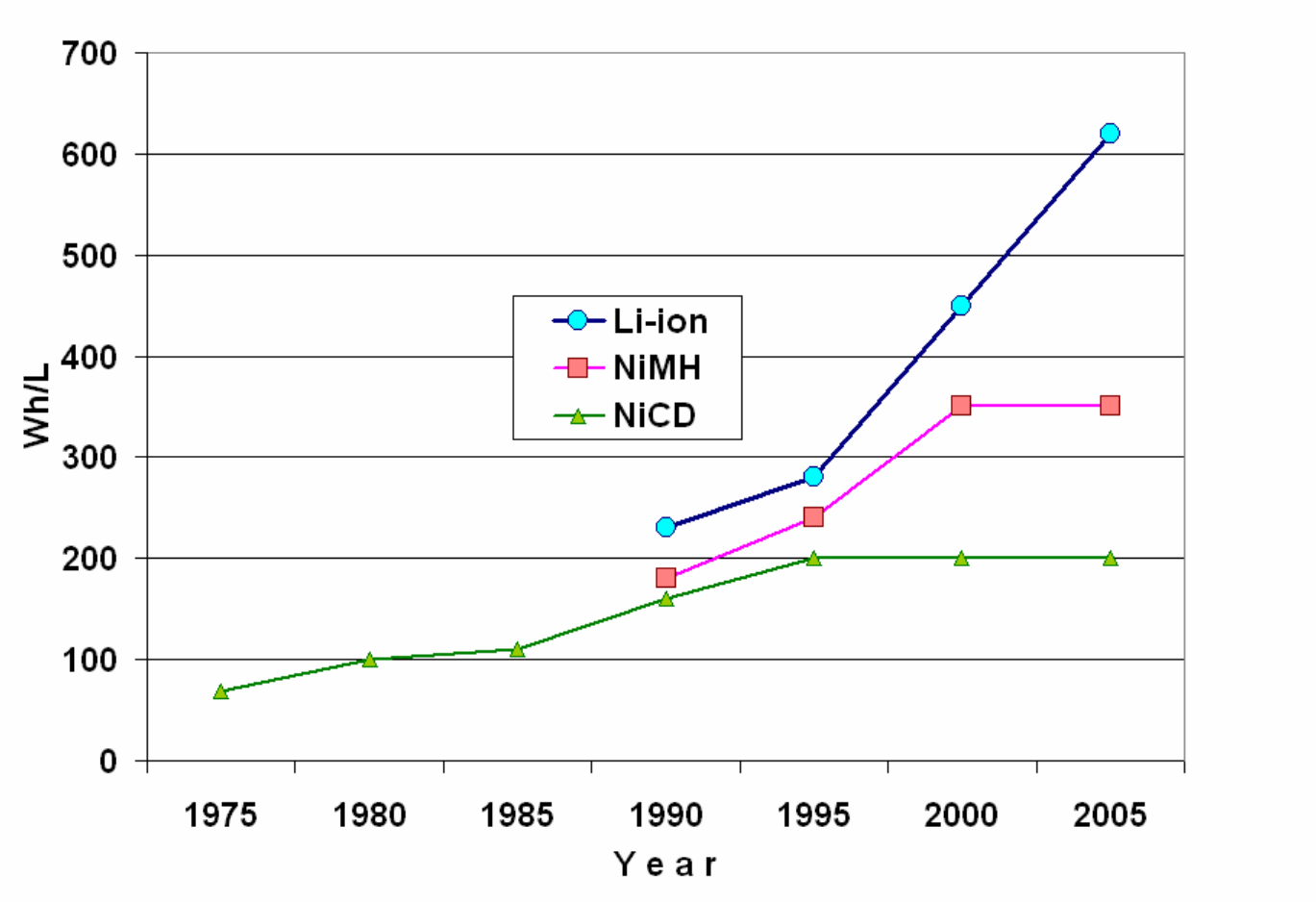


Vs. Past Theoretical & Experimental HEVs, Prius Gets Most From Least Battery Pack



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

To Enable Initial PHEVs, the Key Added Breakthrough was Li-ion Energy Density



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

Conclusions

Evolution of Batteries, Motors, Control Systems and Engines Slowly led to Today's Compact, Efficient Parallel Hybrid Powertrains

Next: The Initial Wave of Successful PHEVs Depends on:

- Adaptation of Parallel Powertrains
- Relatively Small (in kWh and liters) Batteries for PHEVs
- Continued Specific Energy & Energy Density Increases