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Cost-Effective PHEV Range: Battery Costs Versus Charging Infrastructure Costs

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Transportation Research Board Annual Meeting

Session 538 Vehicle Electrification: How Close are We?

Jan. 12, 2010

Washington, DC

Sponsor:
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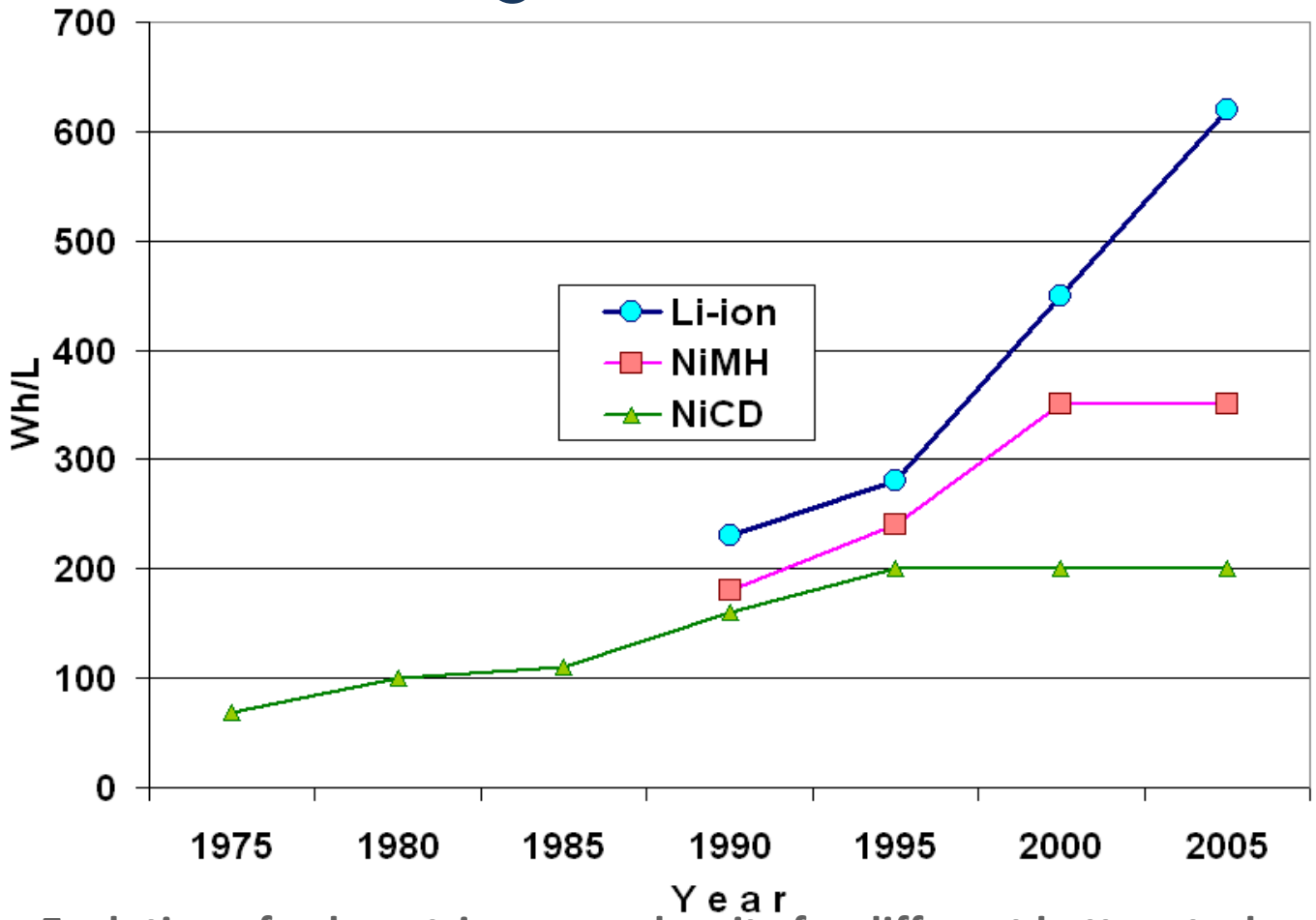
Battery Cost Estimates are Hard to Compare. Many Factors Influence Our $/kWh vs. NAS & Others

- Power to energy ratio proves to be ~ linear with $/kWh in many studies
- Many studies stop at the "factory gate" price to the OEM, ignore retail
- NAS recently estimated that $/kWh for a PHEV10 and E-REV40 would be almost identical; Nelson et al show a sharp drop as PHEV "AER" rises to 40 mi.
- Many studies examine nameplate capacity (100% discharge), when PHEVs will only be able to use a fraction. NAS assumes 50% is the best possible, Nelson et al assume 70-75%. The PHEV Prius may be about 60%.
- Nelson et al assume less cells per pack than in current packs, cutting cost.
- Nelson et al estimate beginning of life power and energy. OEMs probably rate packs conservatively, at end of life power and energy. Beginning of life kWh are (reasonably) asserted to be 20% greater than end of life by NAS.
- Nelson et al estimate very low cost for added power for a PHEV40 (from 40 to 90 kW). NAS may have estimated a larger increase (100 kW vs. 50 in PHEV10).
- Nelson et al assume air cooling. NAS may use air in PHEV10, liquid in E-REV40.

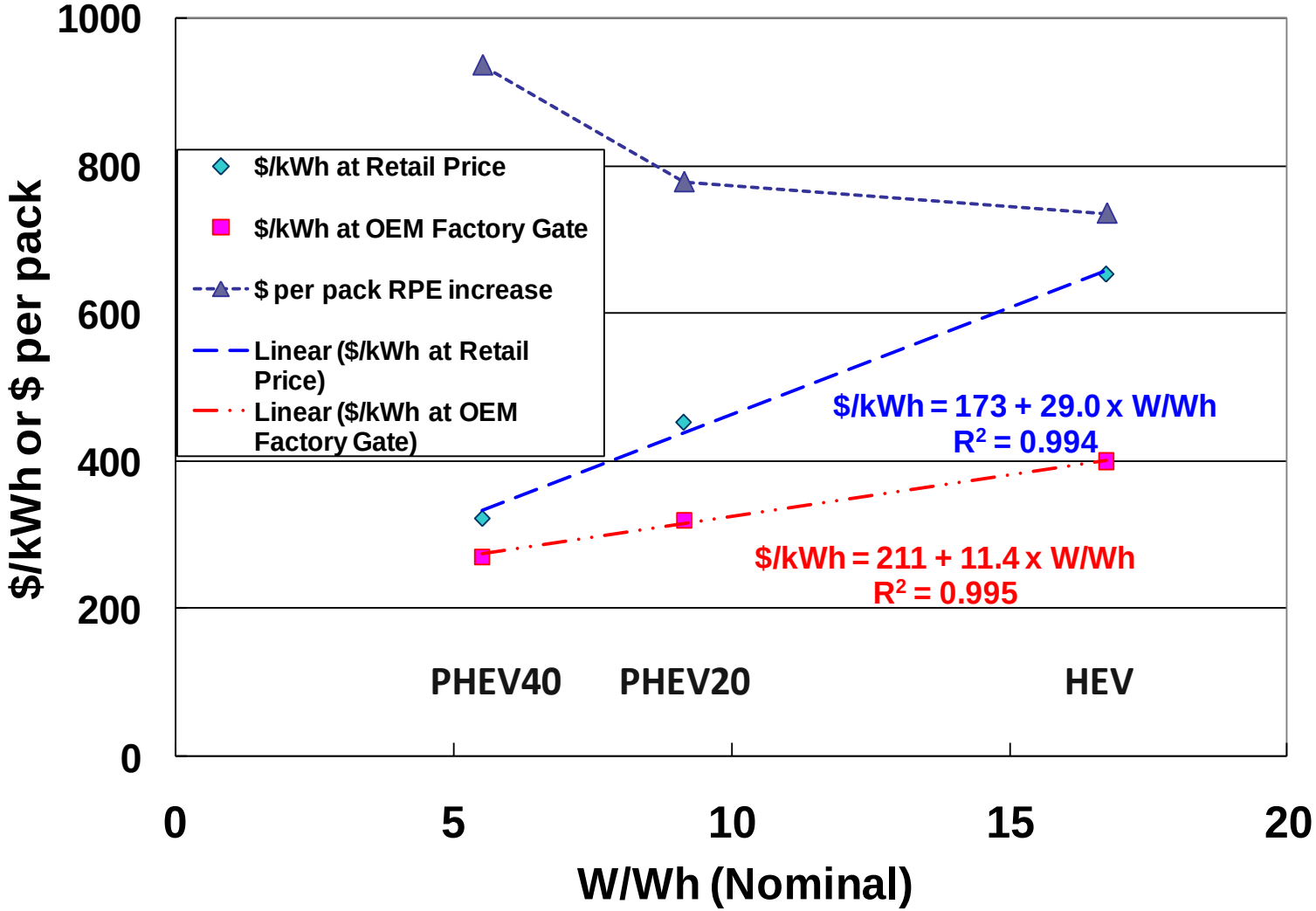
Prior Favored EV Chemistries Wh/L "Plateaued", But A Better One Followed. Li-ion Looks Good Enough. Will it Plateau?



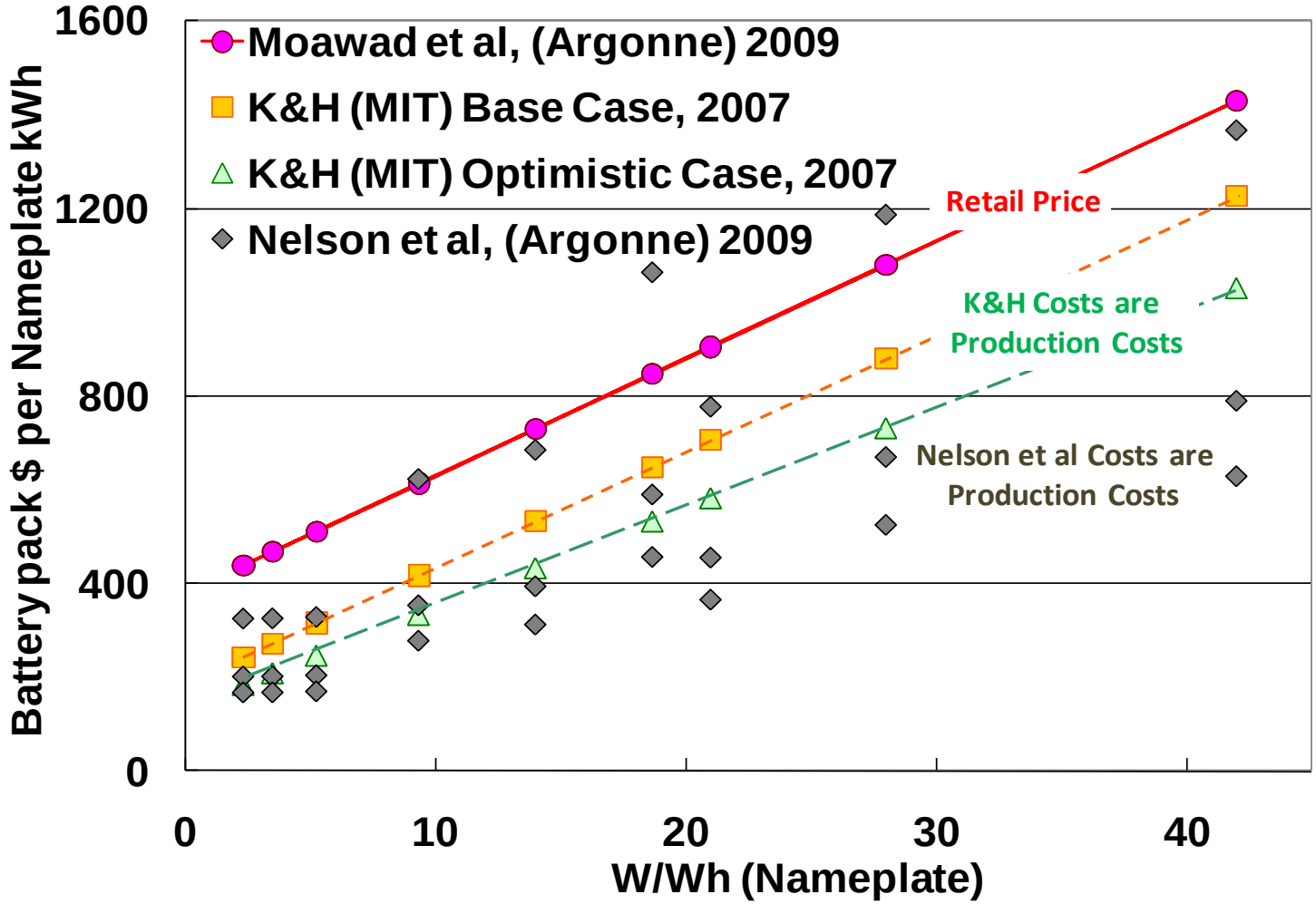
Evolution of volumetric energy density for different battery technologies.

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

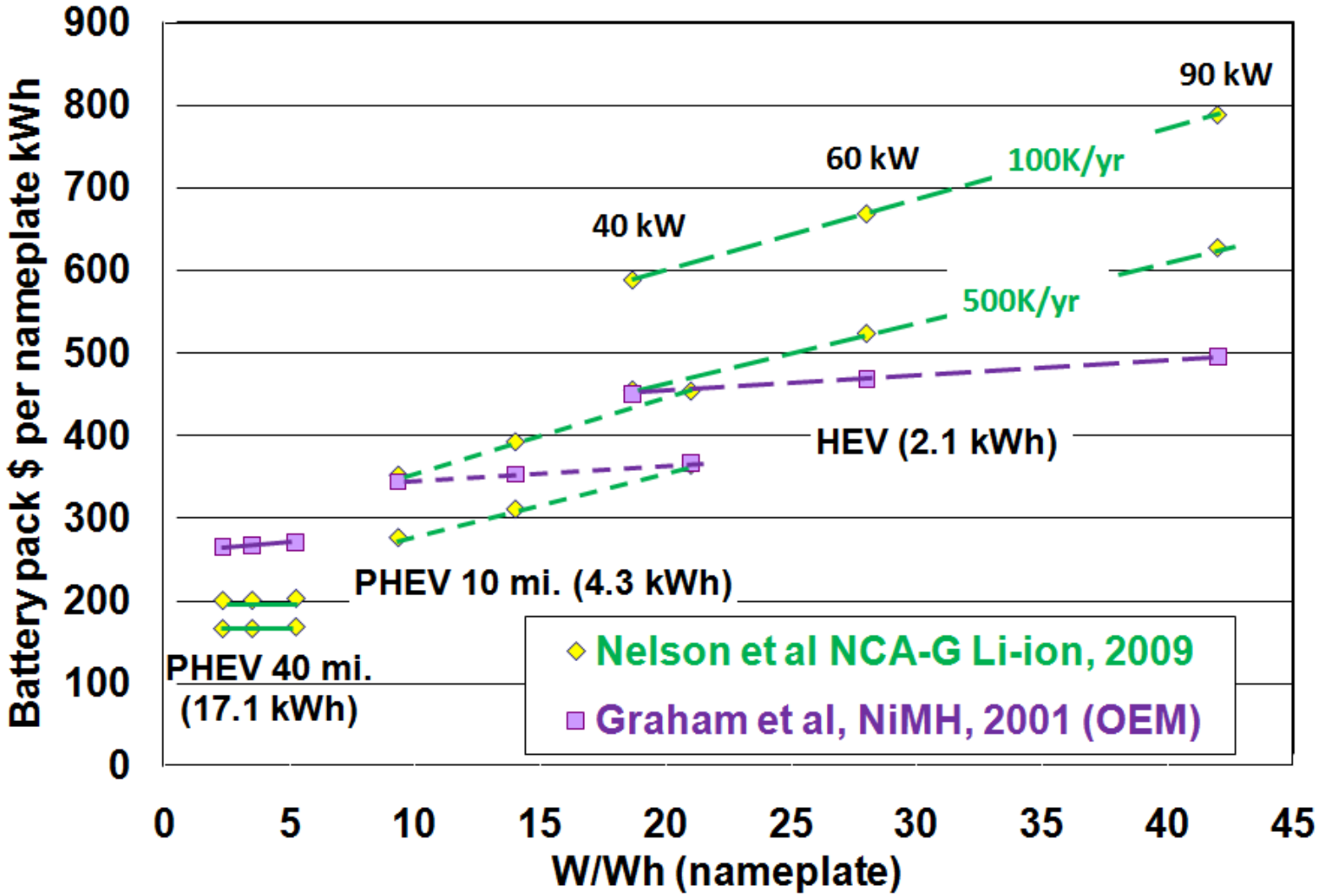
The 2001 EPRI Study Predicted NiMH Pack $/kWh ~ Linear with W/Wh



Nelson et al $/kWh Model Costs Are "Rich" in Detail as Illustrated Here



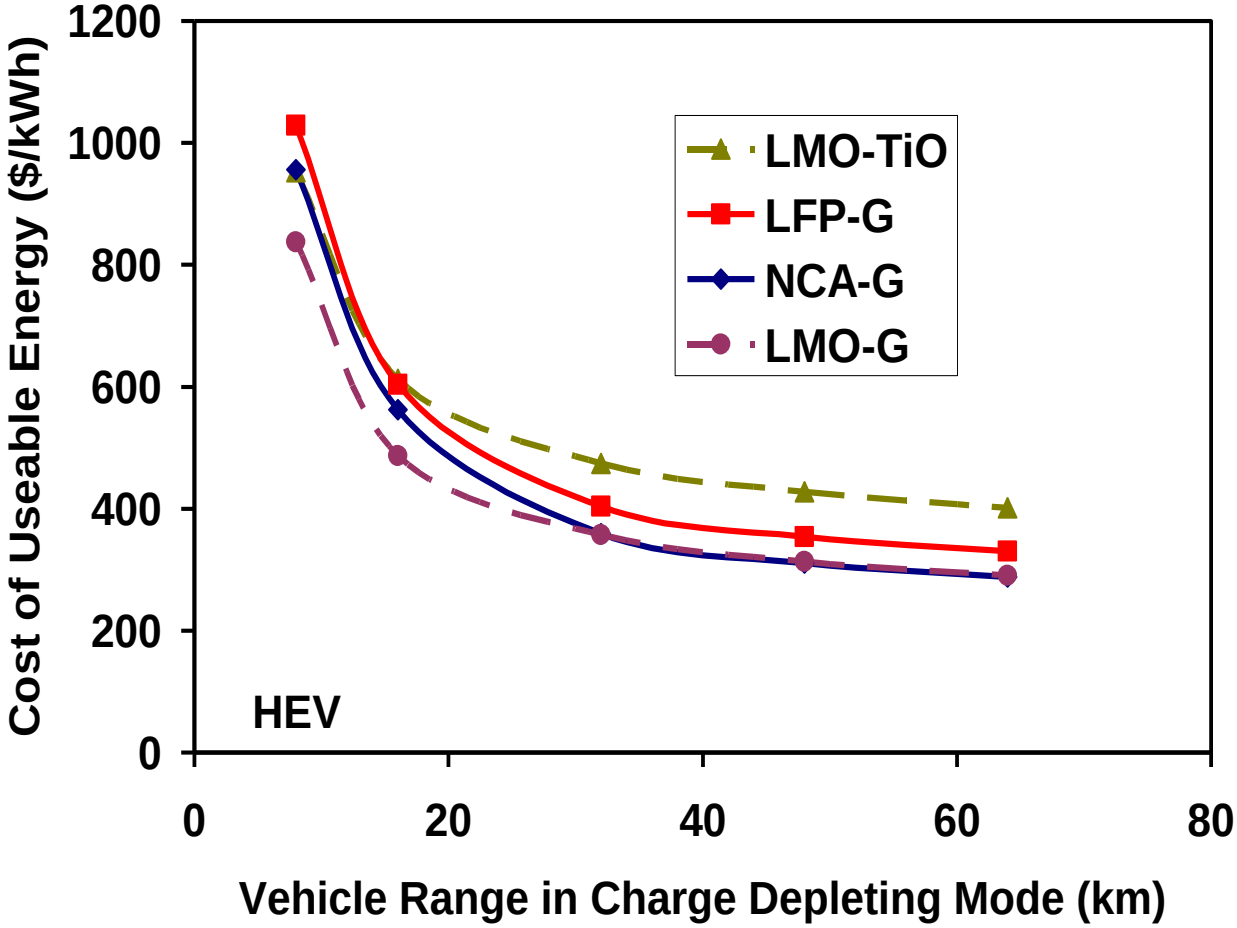
Compared to Graham et al for NiMH, Nelson et al $/kWh Imply Li-ion is Good for High kWh PHEVs



The NAS Study on PHEVs Claims Li-ion is Mature. Four Relatively New Chemistries are Being Investigated for Near-Term PHEVs

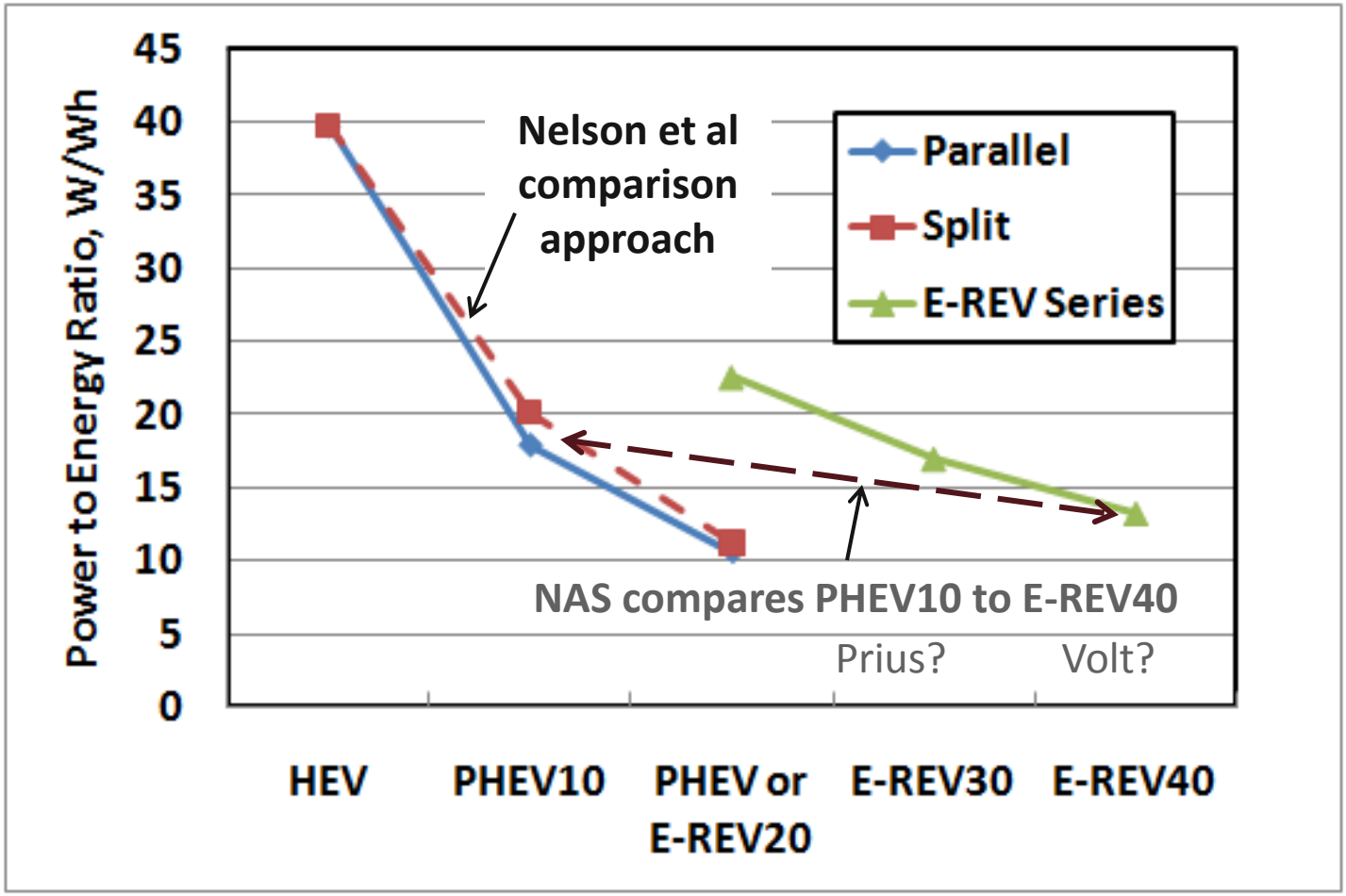
Designation	NCA-G	LFP-G	LMO-TiO	LMO-G
Positive				
Composition	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	$LiFePO_4$	$Li_{1.06}Mn_{1.94}O_4$	$Li_{1.06}Mn_{1.94}O_4$
Capacity, mAh/g	150	155	100	100
Void, Vol.%	32	40	32	32
Negative				
Composition	Graphite	Graphite	$Li_4Ti_5O_{12}$	Graphite
Capacity, mAh/g	290	290	170	290
Void, Vol.%	34	34	40	34
N/P Capacity Ratio	1.25	1.25	1.10	1.25
Impedance at 25% SOC, ohm-cm^2	30	32	10	25
Open Cir. Voltage, V	3.68	3.350	2.514	3.954
Useable Battery Energy, % of Total	70	70	75	70

Holding Peak kW/Pack Constant as "AER" Rises, Nelson et al Show Sharp $/kWh Decline



$/kWh of useable energy. 60 kW (at 25% SOC) packs. 100,000 packs/yr. At constant kW, the cost of energy with increasing CD range would drop sharply - especially for HEVs to moderate-range PHEVs.

If Motor-Generator System & Battery Pack Peak Power Are ~ Constant, W/Wh Drops Fast as Range Increases

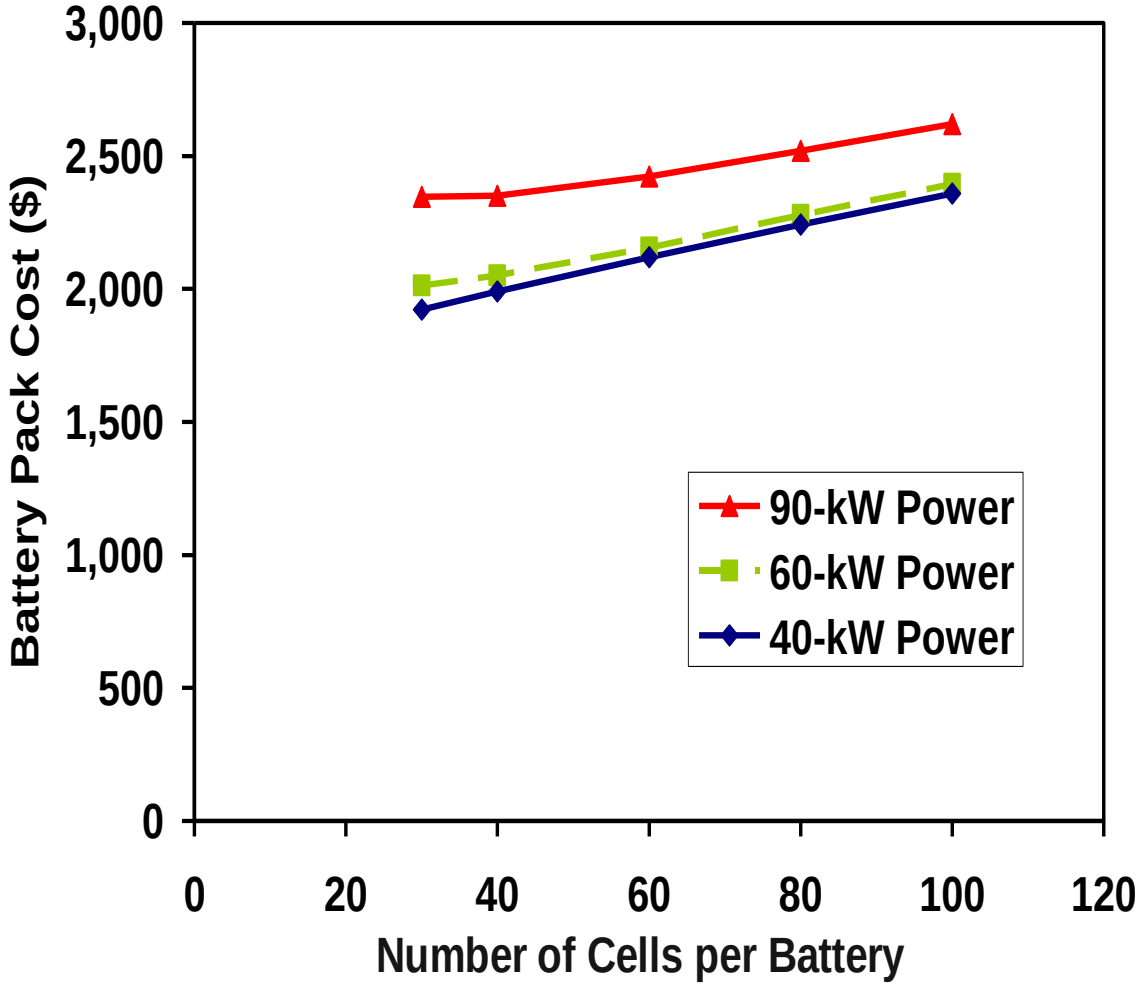


Example – Pack W/Wh in Initial simulations for Argonne/EPRI study of PHEVs

Power to Energy Ratios for the Plug-in Prius and the Volt *May* be Very Close

	Speculated end of life peak kW	Published Nameplate kWh	Implied W/Wh
Prius	21	1.3	16
PHEV Prius	45	5.2	8.6
Volt	122	16	7.6

Nelson et al Estimate that More Cells per Pack Increases Pack Cost



For a set power, more cells per pack increase pack cost.

Cause: cost of formation cycling and state-of-charge control circuits for each cell.

By Projecting 60 Cells Per Pack, Nelson et al Reduce Costs Compared to Contemporary Packs

Pack	Cell Count per Pack
97 Prius NiMH	240
2004 Prius NiMH	228
2010 Prius NiMH	168
2008 Ford Escape NiMH	250
2010 Ford Fusion NiMH	~ 200 (20% reduction)
2011 Volt Li-ion	220
2008 Tesla Roadster EV	6800
Nelson et al - Future Li-ion	60

The Recent Incremental PHEV and E-REV Price Increases Estimated by Argonne CTR Staff Are Well Below those of the NAS

Vehicle	Moawad at al, Argonne EVS-24 Retail Price Equivalent	Moawad et al Increment vs. Conventional	NAS 2015 Probable Assuming 45% Retail Markup Increment vs. Conventional	NAS 2015 Optimistic Assuming 45% Retail Markup Increment vs. Conventional
Conventional	17245			
HEV	20029	2784		
PHEV10	21881	4646	7540	6670
PHEV20	23709	6464		
E-REV30	27487	10242		
E-REV40	29338	12093	20590	16240

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 (< 15 amps delivered)
  - 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 ($35,000+)**

Observations on Implications of Early Information on in-House Infrastructure Costs

- Houses are replaced at about 2% per year. Relatively inexpensive built-in Level 2 charging in new garages will take many years to penetrate a large fraction of garages.
- Retrofit of existing garages to Level 2 charging could double the incremental cost of PHEVs (vs. HEVs) with 10-20 miles of range. Trenching costs to underground cables can be large.
- The cost of smart meters was not included
- For PHEVs, keeping charging simple, at Level 1, seems desirable
- For E-REVs, Level 2 charging retrofits might pay off for very high daily driving in which the vehicle repeatedly returns to the house and recharges during the day.

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).**
  - **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 used $800 for an on-board charger, presumed to be both Level 1 and 2 capable**